

A MICROPROCESSOR BASED CONTROLLER
FOR AN AEROGENERATOR

by

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Thesis submitted for the
Diploma of Imperial College

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London

September 1979

ABSTRACT

The work reported involved the design, construction and testing of a microcomputer controller for an aerogenerator. This machine is for application to the small scale wind energy conversion system being developed at Imperial College. It performs on-line control of an aerogenerator by outputting a gating signal to the three phase half-controlled thyristor bridge which rectifies the output of a wind driven rotational machine. The microcomputer is designed to be used for comparison tests among control studies and to effect load management for the wind energy system. The text also describes aerogenerator control considerations, the microcomputer circuit detail, a list of essential software, a hill-climber control program, and a short operating guide for the microcomputer.

ACKNOWLEDGEMENTS

The author wishes to express particular thanks to the members of the Imperial College Wind Power Group, for all help rendered over the past year. Special mention must be given to the project supervisor Dr. Leon Freris and to the authors' student colleagues Mr. Ian Buehring and Mr. Vassilis Nicoudemou. This time spent on research related to wind power was fruitful and enjoyable and the author hopes to hear of successful future development.

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CHAPTER ONE

INTRODUCTION

Since 1975 research has been underway at the Imperial College of Science and Technology to examine possibilities for a low cost small scale wind power plant intended for domestic use. Under the direction of Dr. Leon Freris, the goals of the project have been defined, and much of significance has been accomplished. The emphasis on small systems has provided the wind power group an opportunity to coordinate several individual task efforts into an integrated plan for a complete functioning wind power plant. The direction which each task follows is known by the others in the group, resulting in an excellent atmosphere for cooperative research. The tasks can be generally defined as three: aerodynamics and wind turbine work, aerogenerator design, construction and testing, and control studies. Of necessity these tasks overlap. The author has been involved for the past 12 months in work associated with system control, and particularly with the application of a microprocessor to control the operation of an aerogenerator.

The small scale wind power plant under study at Imperial College is intended to run singly in a domestic environment. It is not subject to all of the same operation criteria as wind plants intended for synchronous operation with the mains. The Imperial College plant is therefore designed to different priorities, the most important being physical simplicity, low cost, ease of maintenance and high reliability. In keeping to these priorities, the wind plant components have been chosen from existing manufactures when possible and have been purpose built when available products were inadequate or non-existent. For example, the loads envisioned for the finished system are commercially available water and storage heaters; these are ably suited to requirements and are less expensive to install than special purpose units. The aerogenerator, on the other hand was a subject for fundamental research, to design and construct a low speed permanent magnet alternator to be mechanically simple and highly efficient over the wide range of rotational speeds expected in the windmill application.

No available machine was so well suited to the wind power application as to obviate the need for this research investigation.

The notion of applying a microprocessor to control an aerogenerator suggests itself for several reasons. The development of a control circuit for this small windpower system points the way to a standard unit for use with similar small scale plants. Any differences in user requirements can be met by programming changes instead of hardware changes. The microprocessor based controller is versatile, being capable of performing sophisticated or simple aerogenerator control algorithms, load management and even data acquisition in a single unit. The microprocessor based controller has typical solid state reliability, compactness and the potential for lower cost per unit than analog controllers.

To evaluate different control policies it is necessary to have a microprocessor-based machine with input/output capabilities greater than those necessary for a controller which would be applied in a 'standardized' system. The need to do program development work in selecting an optimal control policy requires that the 'development' microcomputer be more sophisticated than the eventual 'on-line' version. The work reported in this thesis involved the design, construction, testing and programming of a microcomputer, toward the eventual goal of identifying a minimum system for repeated application in small scale wind power systems. The microcomputer task has more work associated with it than could realistically be accomplished in one year; much is left to be done, not only to refine control strategies but also to accomplish such things as expanding the system to acquire data from an unmonitored site, a capability that would be valuable in long term testing and evaluation of wind plant performance.

The scope of the work undertaken over the past year reflects the desire of the author to pursue two goals: 1) to acquire an intimate working knowledge of microprocessor digital circuitry; 2) to learn the various engineering variables associated with wind power. Much time has gone into maintaining the legibility and simple exterior

design of the microcomputer so that it will be more readily useable by future students working on the wind power project.

Beyond the creation and testing of the microcomputer, the author wrote the minimum software necessary to make it operable and also wrote programs for control of the firing angle signal to the rectifier of the aerogenerator output. Most notable of these was a hill climbing controller for which input signals were taken from an analog model of the wind power station at Silwood Park, developed by Ian Buehring on an EAI TR-48 analog computer. The next milestone in this development is on-line digital control of the windmill at Silwood Park, using this hill climbing strategy. The author has also studied the possibility of creating an adaptable control algorithm for aerogenerator load management. All of these topics are recorded further in subsequent chapters.

CHAPTER TWO

A LOW COST, SMALL SCALE WIND POWER SYSTEM FOR HEATING DOMESTIC PREMESIS

Below is a description of the Imperial College wind power project in moderate detail, to act as a background for further discussion of aerogenerator control.

2.1 WIND POWER POTENTIAL IN BRITAIN

The western coastal areas of the British Isles are known to be well suited to the exploitation of wind energy resources. Sites which could provide 4000 KWh per KW capacity at 30mph wind speed are estimated to number in the hundreds.(1) In fact Britain is generally an excellent location for wind power installations; thousands of sites can be identified where year round availability of the wind and its flow over the land make construction of wind power plants attractive. Most of these are not suitable for large scale plants, because of construction difficulties and transmission requirements in isolated sites, technical problems associated with synchronous operation, high capital cost necessary for large windmills or the necessity of manning these large facilities. Large scale synchronously operated wind generators will no doubt be important to future utilization of wind power in Britain, but smaller sets can provide important local supplies of energy if technology of this level is available. The body of recent research carried out in British universities on small scale wind power systems has advanced the feasibility of these systems by identifying or developing reliable and mechanically simple wind rotor/generator combinations. Small scale in this context means individual household applications in rural areas and the outer fringes of suburbia. (2)

This sort of application is becoming ever more attractive economically as the costs of conventional energy sources rise. This factor, in concert with increasing concern about the long term consequences of consuming non-renewable sources, and the effects of this consumption on environment, have caused a resurgence of interest in alternative energy sources. This renewed interest has focussed

attention on providing local supplies of energy for heating and electricity, to at least supplement utility sources. As the United Kingdom is so well blessed with areas of high wind activity it is logical to utilize this available energy where possible. It is to this end that the wind power group at Imperial College is investigating small systems.

2.2 TECHNOLOGICAL ADVANTAGES ATTENDING SMALL ISOLATED WIND POWER SYSTEMS

The decision to work with small scale wind plants immediately simplifies the electrical requirements of the aerogenerator system. It is no longer necessary to maintain a constant frequency/voltage output, and the efficiency with which energy may be extracted from a given wind regime is therefore increased. It is possible in isolated systems to use low speed alternators with lower nominal output voltages than are acceptable for synchronous systems. In general, small systems are more attractive for geographically remote sites or for local wind power generation since they are mechanically and electrically simple, easily maintained and adaptable to supply a variety of load requirements.

2.3 WIND POWER RESEARCH AT IMPERIAL COLLEGE

The philosophy of the wind power research effort at Imperial College, its scope and objectives, are presented in reference 2. The work reported took place over the period 1975 to fall 1978, examining and comparing various configurations for wind energy conversion systems for heating domestic premises. The conclusions drawn there helped to identify a wind power system for intensified development. The assembly and test of a wind generator yielded valuable information for future work, and a second generation wind turbine/aerogenerator is now in testing. Reference 2 also presents a cost function analysis for small wind plants, based on experienced and projected expenses and assumptions regarding the design of the wind plant and the available wind energy.

2.3.1 PROJECT SCOPE AND FACILITIES

Over the past year the wind power project at Imperial College has employed three full time postgraduate students under the auspices of Drs. Leon Freris and Hugh Bolton. The end product of the work is to be a wind power system (wind rotor, aerogenerator, control) that can be easily manufactured and sold as a standard unit. It is intended to supply purely resistive heating loads such as water tanks and storage radiators or central heating units. A block diagram of the wind energy conversion system is shown in Figure 1. As mentioned above the project is divided among three tasks, which are described below.

2.3.1.1 Wind Rotor and Field Testing

This task is primarily the work of Ian Buehring and it has encompassed responsibility for aerodynamic studies on wind rotor designs and construction and operation of the field testing site at Silwood Park, near Ascot. This part of the project requires knowledge of the entire system design and expertise of some depth in all manner of engineering, mechanical, electrical, aerodynamic. Mr. Buehring designed the test facilities at Silwood Park, which include a seven meter lattice construction tower on which to mount wind rotor/aerogenerator combinations, and a remote hut equipped with instrumentation for operating and monitoring the windmill under test. The tower can be winched to the ground for alterations to the aerogenerator set and for access to auxiliary equipment such as anemometers. This versatile test site is used to evaluate new machines, wind rotors and control schemes.

The present set of wind rotor blades have a cambered plate section which was chosen based on the predicted Reynolds number for this 2.5 meter diameter size. This blade section has an acceptable power coefficient - tip speed ratio characteristic and the rotor is inexpensive and easy to make. The manufacture of the blades was done by Mr. Buehring. Other blades to be tested on site are a single blade wooden rotor and a three blade sailing rotor with foam tips. Mr Buehring has also provided overspeed

protection and orientation control for the aerogenerator/rotor set, along with analog load control for the first generation wind plant.

2.3.1.2 Machines

Mr. Vassili Nicoudemou has done research on small wind powered electric generators and systems under the supervision of Dr. Hugh Bolton. The culmination of this work has been to design, build and test a low speed permanent magnet alternator purposely suited to be driven by a wind rotor. (3) This machine is currently being tested (September 1979) at Silwood Park. The permanent magnet alternator has a useful role to play in small wind plants feeding isolated loads where there is no requirement for stringent frequency or voltage control. (3) Nicoudemou reports some of the advantages of permanent magnet alternators: 1) they do not require an external source for excitation; 2) no transmission (gear box) is required; 3) gives power at high efficiency over full range of speed; 4) is robust and able to withstand severe adverse environmental conditions; 5) low maintenance; 6) long life. Disadvantages include relatively high (compared to wound field alternators) cost per rated power, non-controllable voltage output and the requirement for careful matching of alternator, windmill and load. If the quoted disadvantages are accepted or can be dealt with, then this machine is seen to be very attractive for wind power application. This innovative design has an appealing simplicity and the efficiency and ruggedness necessary for a small scale wind power system.

2.3.1.3 Control Studies

Wind power plant control is the primary subject of this thesis; the desire to implement a controller for the system of Figure 1 is the impetus for this research. Reference to the block diagram will show that the control needs of the system are twofold: 1) Controller A holds an algorithm by which to vary the gating signal to the aerogenerator output rectifier. 2) Controller B performs load management for the several elements of the domestic heating capacity. These two controllers are conceptually independent but they are contained within a single microcomputer. Most of the effort spent on this task has been toward providing a microcomputer tailored to perform firing angle and load switching

control for the facility at Silwood Park. A detailed description of the computer circuit is found in Chapter 6.

2.3.2 CONTROL PROVISION

Control capability for the wind energy conversion system can be worked up in various ways, depending on the size of the system and the highest acceptable cost for the controller. In the simplest case, rotational speed control can be accomplished by switching series resistance elements in or out of the load circuit. This policy has the advantage of being easy and inexpensive to implement (relays can be used). But there is a penalty associated with using this system: it is not possible to use off-shelf heating loads, as these are usually not easily segmented to present a wide range of resistances to the aerogenerator output. It is also likely that more than one segmented load will be necessary for those periods of high wind activity when the primary heater is fully charged. (4)

The control policies applicable to the system of Figure 1 are more sophisticated than load switching and involve the use of a three phase half controlled thyristor rectifier to vary the effective load as seen from the terminals of the aerogenerator. This scheme emphasizes flexibility and controllability at the expense of simplicity and the controller is almost certainly more expensive than a load switcher. In fact by choosing to build a microcomputer controller it becomes possible to evaluate control policies of all types; this versatility was a major consideration in the decision to use a microprocessor based controller.

2.4 PROSPECTUS FOR FUTURE WORK

Development of the small scale wind energy conversion system has returned much useful technical knowledge, including the novel design for a low speed permanent magnet alternator. As the field station at Silwood Park becomes more fully equipped to test aerogenerator control and loading policies it will be possible to evaluate rotor-machine combinations over extended test time periods. The work done so far has identified one potential commercially viable

system and this data is valuable to anyone interested in the manufacture of wind power plants. Continuing research will include the trial of more wind rotors, some of which have been made at the college. Future control developments will include further tests of control policies with the microcomputer interfaced to an analog model of the aerogenerator/rotor set, application of the controller at Silwood Park, writing of an adaptive controller program for load management and the development of a minimum system circuit using the latest microprocessor technology.

CHAPTER THREE

AEROGENERATOR CONTROL CONSIDERATIONS

This chapter contains a discussion of those characteristic properties of wind power systems which become basic design constraints in the implementation of aerogenerator control. The first two sections review the operating conditions at which an aerogenerator extracts power from the wind optimally. These are general statements applicable to any wind power system. The middle two sections describe several possible control systems for the Imperial College aerogenerator. The chapter ends with a description of the necessary hardware to achieve aerogenerator control, as chosen for the Imperial College system to execute control policies applicable to it.

3.1 POWER COEFFICIENT AND TIP SPEED RATIO

For any wind rotor it is possible to generate by theoretical analysis a characteristic curve of the torque coefficient (a quantity defined by aerodynamic analysis) as a function of the rotor tip speed ratio:

$$C_q = \frac{Q}{\frac{1}{2} \pi r^3 v^2 \rho} = \frac{2Q\lambda^2}{\rho \pi r^5} \quad (3.1)$$

where C_q = torque coefficient, Q = rotor shaft torque, ρ = density of air, r = rotor radius, v = wind speed, λ = rotor tip speed ratio and ω = shaft rotational speed. This curve takes the form shown in Figure 2 as calculated for the cambered plate rotor blades now at Silwood Park; this characteristic is in the process of being verified experimentally. The rotor tip speed ratio can be expressed as:

$$\lambda = \frac{\omega r}{v} \quad (3.2)$$

This dimensionless quantity is particularly important because it is one of the first parameters chosen in the design of a rotor/generator set. Having decided upon a tip speed ratio value, the blade design and transmission/machine combination are subsequently chosen to operate as closely as possible to the prescribed λ value. The power coefficient

of the rotor can be expressed as:

$$C_p = (C_q)(\lambda) \quad (3.3)$$

$$= \frac{Q}{\frac{1}{2} \pi r^3 v^2 \rho} \cdot \frac{\omega r}{v} \quad (3.4)$$

$$= \frac{Q}{\frac{1}{2} \pi r^2 v^3 \rho} \quad (3.5)$$

This dimensionless value is the ratio of the power extracted from the wind by the rotor to the total available power passing through the rotor at any instant. This coefficient has a theoretical maximum value less than one, which can be shown by developing the simple momentum theory of wind power:

$$P = \rho A V (V_1 - V_2) V \quad (3.6)$$

where V = wind speed at the rotor, V_1 = wind speed upwind of the rotor, V_2 = wind speed downwind of the rotor and A is the area swept by the rotor. Further,

$$P = \rho A V^2 (V_1 - V_2) \quad (3.7)$$

$$= \rho A \frac{V_1 + V_2}{2}^2 (V_1 - V_2) \quad (3.8)$$

$$= \frac{\rho A V_1^3}{4} ((1+\alpha)(1-\alpha^2)) \quad (3.9)$$

$$\text{where } \alpha = \frac{V_2}{V_1}.$$

To maximize this function:

$$\frac{dP}{d\alpha} = \frac{d}{d\alpha} (K(1-\alpha^2 + \alpha - \alpha^3)) = 0 \quad (3.10)$$

$$= -2\alpha + 1 - 3\alpha^2 = 0 \quad (3.11)$$

Using the quadratic formula:

$$\frac{dP}{d\alpha} = 0 \text{ when } \alpha = \frac{1}{3} \text{ or } V_2 = \frac{1}{3} V_1$$

This states that the maximum power which can be extracted by a given wind rotor is:

$$P_{\max} = \frac{\rho A V_1^3}{3} ((1+\frac{1}{3})(1-\frac{1}{3}^2)) \quad (3.12)$$

$$= (\rho A V_1^3)(8/27) \quad (3.13)$$

Therefore the maximum possible power coefficient is:

$$C_p \text{ max} = \frac{P}{P_{\text{max}}} = \frac{(\rho A V^3)(8/27)}{(\rho A V^3/2)} \quad (3.14)$$

$$= 16/27 = 0.593$$

Since no windmill is ideal, a power coefficient of 0.593 is not attainable in real windmill systems. A typical value of $C_p \text{ max}$ for a propeller type rotor such as that being tested at Silwood Park is in the range 0.3 to 0.4.(5) Figure 3 shows the theoretical $C_p(\lambda)$ curve for the cambered plate rotor; this plot is acquired by multiplying $C_p(\lambda)$ by λ and plotting the result as a function of λ . Examination of this characteristic suggests that the rotor is best operated at one particular value of tip speed ratio, λ_{max} , as this provides the highest power coefficient C_p and therefore the optimal extraction of energy from available wind. In general, aerogenerator control schemes for small scale systems are in some way intended to maintain a constant tip speed ratio (λ_{max}) by controlling the shaft rotational speed as a function of the wind speed. This can be accomplished in a variety of ways depending on the capabilities of the rotor/machine/load combination.

3.2 RECONCILING THE CUBE LAW INPUT

There is another way to consider the problems associated with optimal extraction of power from available wind; this discussion makes use of the shaft power vs. shaft speed characteristic for a typical wind rotor (Figure 4). Equation 3.6 can be approximated over a wide range of wind speeds by:

$$P_w = K_v^3$$

where P_w = wind power. This cube relationship between wind speed and shaft power is shown on Figure 4 as a line connecting the locus of maximum power points along the curves showing shaft power as a function of shaft speed for different wind speeds. This is true for most wind rotor geometries and can be considered an empirical property of wind turbines. This shaft power is to be converted to

electrical power which will be consumed in most small scale wind plants by resistance or battery charging loads. In general:

$$P_1 = VI = \text{electrical power absorbed by the load} \quad (3.16)$$

The generator terminal voltage is approximately proportional to the shaft rotational speed as:

$$V_t = a \omega \quad (3.17)$$

therefore:

$$I = \frac{V_t}{R_1} = \frac{a\omega}{R_1} \quad (3.18)$$

where R_1 = load resistance and I is the current flowing out of the machine terminals. By combining 3.16, 3.17 and 3.18:

$$P_1 = \frac{a^2 \omega^2}{R_1} \quad (3.19)$$

If the assumption is made that most of the shaft power will be transmitted into load power (neglecting other losses) then:

$$P_1 = P_w \quad (3.20)$$

therefore from 3.15 and 3.19:

$$\frac{a^2 \omega^2}{R_1} = K v^3 \quad (3.21)$$

and since the desired constant tip speed ratio is:

$$\lambda_{\max} = \frac{\omega r}{v} \quad \text{or} \quad \omega = \frac{\lambda_{\max} v}{r} \quad (3.22)$$

then 3.21 becomes:

$$\frac{a^2 \lambda_{\max}^2 v^2}{r R_1} = K v^3 \quad (3.23)$$

or

$$\begin{aligned} R_1 &= \frac{a^2 \lambda_{\max}^2 v^2}{K v^3 r} \\ &= \frac{a^2 \lambda_{\max}^2}{K r} \cdot \frac{1}{v} \\ &= \frac{\beta}{v} \quad \text{where} \quad \beta = \frac{a^2 \lambda_{\max}^2}{K r} \end{aligned} \quad (3.24)$$

This suggests that the load resistance should be varied roughly as the inverse of the wind speed to maintain the constant tip speed ratio.

This analysis illustrates the problem of matching the cubic characteristic of the wind rotor shaft power to the square law load characteristic of an electrical resistance. This can be appreciated in a useful qualitative way by examining the load curves for two values of resistance in Figure 4. To operate at the peak power extraction point for varying wind speeds it is necessary to change the magnitude of the load resistance. This action shifts the operating point of the rotor/generator set nearer to the ideal $P = k\omega^3$ line. It is desirable to operate to the right of the peak power point (toward higher shaft speed) since lower shaft speeds risk stalling the rotor, particularly at low wind speed. At the rated wind speed of 9 m/s, resistance 1 would be chosen for the load, while at the lower speed of 4-6 m/s, resistance 2 is preferred. The amount of control available is a function of the number of available load resistances.

3.3 AEROGENERATOR CONTROL FOR CONSTANT AND VARIABLE LOAD RESISTANCE

From here forward several assumptions will be made about the wind energy conversion system: 1) variable pitch rotors will not be discussed since the rotor now under study is fixed pitch. Unless otherwise noted 'the rotor' refers to the 2.44 meter diameter three blade cambered plate, horizontal axis rotor now at Silwook Park; 2) variable field excitation machines will not be discussed, and unless otherwise noted the aerogenerator referred to is a three phase low speed permanent magnet, external rotor machine rated at 5kW at 1500 rpm.

There are two schemes for aerogenerator control which deserve particular mention, as these are most relevant to the Imperial College wind power project. One of these, load switching, has been treated above in section 3.2; the other concerns a method of constant load resistance control using a three phase half controlled thyristor rectifier

(see Figure 2).

Figure 5 is a schematic representation of the three phase half controlled thyristor rectifier, which is used to convert the three phase a.c. aerogenerator output to d.c. for the load.(6) At a delay angle defined as zero degrees, the three thyristors are fired in such a way that they work like diodes in the circuit; the rectifier output is a d.c. voltage level with a ripple frequency six times that of the generator rotational frequency. The $\alpha = 0$ condition allows the maximum power to be transmitted through the rectifier for a given three phase sinusoidal input voltage. As the firing angle is increased from 0° the average d.c. output voltage falls (see reference 7) as less current and therefore less power flows through the rectifier. At $\alpha = 180^\circ$ the current passing through the rectifier approaches zero and the aerogenerator effectively runs unloaded. By varying the firing angle signal to the bridge when a constant wind speed is impinging on the rotor, the shaft rotational speed can be controlled; $\alpha = 0^\circ$ represents the fully loaded condition, while at $\alpha = 180^\circ$ the shaft will accelerate until the rotor experiences no further torque from the available wind. This is the proper operating mode for the rectifier when the wind speed is below the cut-in value. In this condition, no power is applied to the load and the machine is able to speed up, subject to only frictional retarding forces.

An expression for the output voltage for each phase of a three phase half controlled thyristor rectifier is given by:

$$V_d = \frac{2 V_{ac}}{\pi} (1 + \cos \alpha) \quad \text{for } \frac{L}{R} = 0. \quad (3.25)$$

where V_d = average direct rectifier output voltage, V_{ac} is the peak input voltage and α = the delay angle.(7) This can be re-expressed as:

$$V_d = V_{do} (1 + \cos \alpha) \quad \text{where } V_{do} = \frac{2 V_{ac}}{\pi} \quad (3.26)$$

V_{do} is V_d with $\alpha = 0$. It is straightforward to express

the power flowing through the rectifier as a function of α :

$$P_d = \frac{3V_d^2}{R_1} = \frac{3V_{do}^2(1+\cos\alpha)^2}{R_1} \quad (3.27)$$

where R_1 is the load resistance. For an initial condition wind speed, increasing α will cause wind energy to be stored in rotational inertia of the rotor/machine set; decreasing α will cause this power to flow through the load resistance. By thus regulating the delay or firing angle α it is possible to draw more or less of the available wind power from the aerogenerator and in this way to effect an optimal controller. This rectifier/constant resistance scheme was chosen because it simplifies the geometry requirements of the load, although the controller itself is more sophisticated than it need be for a load switching scheme. It is more attractive to utilize existing heating loads than to purpose build units, especially since the load is that part of the system most familiar to the system owner. In most potential small scale wind power applications it is desirable to use existing equipment as much as possible; the economy of such a system is expected to offset the additional expense associated with a more versatile controller.

3.4 USE OF WIND SPEED KNOWLEDGE

Having seen that it is desirable to control the tip speed ratio of the aerogenerator in Figure 2, the question remains of how best to choose a specific control policy. In general these control policies belong to one of two groups: those that require information about the wind speed and those that do not.

To gather advance information about wind before it passes through the plane of the rotor requires that an anemometer be placed upstream of the rotor. By using this information, the firing angle of the rectifier can be increased or decreased to respectively increase or decrease the shaft speed ω in anticipation of the approaching wind. The success of this scheme largely depends on the behavior

of the time constant of the rotor/machine set, which must be short enough in all expected operating wind speeds to allow effective control to take place. The shape of the curve defining the rotor/generator set time constant as a function of the wind speed is useful to know; as the wind speed increases, the time taken by the wind to pass from the upstream anemometer to the wind rotor decreases, and less time is available to prepare the rotational system for optimal extraction of the energy available in upstream wind. It might also be advantageous to filter the advance wind information, particularly in gusty conditions.(8) When using prior knowledge of the wind speed it is possible to implement either a bang-bang controller (firing angle equals either zero or 180 degrees) or a more sophisticated algorithm which controls α over the full range of 0-180 degrees. These control routines might consist of a calculation or look-up routine that has been previously developed to take account of the experimentally determined physical response of the system. Alternatively the control routine may rely completely on real time data inputs.

To maintain a constant tip speed ratio which offers the highest possible power coefficient, one control possibility calculates the instantaneous value of α (see Eqn. 3.2). This requires two real time input signals: ω , which might be a voltage output tachometer, and v , the present wind speed signal from an anemometer. To make use of prior wind speed information, this anemometer may be mounted at hub height on a long boom in the airstream upwind of the rotor. A criterion for varying the firing angle signal may be established which uses a calculation of α on a continuous basis. This scheme has several variables to consider: placement of the anemometer, choice of firing angle signal algorithm and optimum tip speed ratio, assumptions regarding the rotational time constant, etc. This sort of system is the most sophisticated envisioned for the domestic scale wind plant and it demands more than one input variable signal. A particular disadvantage is that anemometers are quite expensive, therefore mounting one or more of these on a wind plant would increase the cost and physical complexity of

the installation. It is desirable to identify a control strategy which affords the best compromise between optimal extraction of available wind energy and cost of the optimal controller. If the most complex controller is also that which enables the maximum possible energy to be extracted from a given wind regime, this will not automatically exclude alternatives. If a control system can be built which is simpler, more reliable, more easily maintained and less costly in the first instance than the complex one, then a slight sacrifice in performance will be acceptable. Generally speaking, controllers which do not require advance information of the wind fall into this simpler category.

3.5 CONTROLLERS NOT REQUIRING WIND SPEED INPUT

By eliminating the necessity for wind speed knowledge, the need for anemometers is obviated. It is less expensive to build the wind power plant if the controller can operate solely on inputs from instruments like a tachometer and power meter. Such a control policy takes account of the curves of Figure 4 and causes the shaft speed operating point to remain as close as possible to the $P \propto \omega^3$ line (see section 3.2). Since the maximum rotor power characteristic is predetermined, controller A of Figure 1 can be programmed to maintain a particular shaft speed based on a measurement of the generator output power.

Without wind speed knowledge, direct calculation of the tip speed ratio and power coefficient are not possible, but the mechanical design of the wind plant is simpler. This sort of system is being tested at Imperial College, although the existing controller is capable of executing routines which use wind speed information.

The most important inputs to the controller, excluding those necessary for load management, are the shaft speed and the load power. Control routines have been written which use only these inputs and adjust the firing angle output signal voltage by increments with a full scale resolution of 256. A bang-bang control policy has also been written which sets the firing angle signal to either 0° or 180° . These algorithms have different internal variables than

routines which use advance wind information. These are:

A) for the hill climbing controller: 1)sampling rate;
2)step length; 3)step height (degrees); 4)cut-in rotational speed; 5)cut-out firing angle; B)for the bang-bang controller, as for A except that there is no step height variable. The flow charts and programs which accomplish these schemes on the microcomputer are listed in Appendix C.

CHAPTER FOUR

LOAD MANAGEMENT

4.1 NATURE OF THE WIND POWER PLANT LOAD

For all of the small scale domestic wind power applications being considered, it is useful to store the incoming wind energy. This makes the random wind energy source more useful in situations where demand for energy follows a predictable pattern. It also allows all of the available wind energy to be used, avoiding the dumping of energy which is in excess of current demand. Direct use of wind energy, without storage, is not particularly efficient since demand will not often coincide exactly with the available incoming power. Energy storage devices also simplify the task of the optimal controller if the capacity of the store is always greater than the available energy. In a domestic environment there are several plausible energy storage mediums but the most widely used form is heat, stored in solid mass or water. In the United Kingdom the storage radiator and hot water heater are the most common forms of domestic energy store. These units are available in various styles and capacities; they have been considered for use as loads with the wind power plant.

To the potential user, the most important factors affecting the choice of a space storage heater are: competitive installation costs, acceptable annual fuel costs, continuous comfort capability, unobtrusiveness and automatic operation.(9) It is attractive to use these heaters as load for the aerogenerator because: 1) the installation cost of the wind energy system can be reduced, since the expertise needed to install storage heaters is always locally available; 2) annual home fuel costs can be reduced to the extent that wind energy replaces energy that must be purchased otherwise; 3) when using a well conceived control system, the wind energy supply can operate automatically and unobtrusively to provide a necessary level of heating comfort.

Storage space heaters and water heaters have similar charge and discharge characteristics but the duty cycles

they perform are different. For the purpose of absorbing wind energy the water heater is preferred for several reasons: 1) all domestic environments require hot water year-round, while space heating is usually a seasonal requirement; 2) on a short term basis, the use pattern for hot water is more predictable than that of space heating, since the latter depends on weather conditions. It is however true that when the demand for space heating is normally highest, in the winter months, wind activity is also high. In tandem, these two heat storage devices make up a useful double-duty load for an aerogenerator.

The need for energy storage capacity in a wind energy conversion system is pointed out by many authors (10,5,2) and the case in favor is stated convincingly in reference 2. Here is noted an increase (from 42% to 72%) of the percentage of time for which the power output of a particular wind generator exceeds the average annual power when a storage capacity of 24 hours is added to the system. This sort of evidence seems to justify the use of storage capacity even in installations where mains electricity supply is available. In completely isolated locations, storage capacity is an essential element of the wind energy system, and such capacity is also attractive as a partial replacement for mains electricity supply. Assuming that wind energy is to be transformed to electricity by an aerogenerator it is possible to use the same resistive heating loads with both the mains and wind energy supplies. These sources cannot be applied simultaneously to the same load, but by enforcing some scheme of load management they can be alternatively used to satisfy user demand and also to make optimum use of the available wind energy.

Figure 6 shows the sort of system which would use both mains electricity supply and wind energy to feed the same loads. This is a more detailed representation of Figure 1 to include a microcomputer which executes control functions and switches water and storage heating loads. There are several notable features of this arrangement of components: 1) the loads perform double duty, being charged by the wind when the energy is available and by the mains

during calm periods; 2) the water heater has two elements, which can be selected separately, the upper one to quickly charge the small volume of water at the top of the tank and the lower one to charge the whole tank; 3) the control and load switching system is entirely electric, including thyristor switching, for long life and high reliability; 4) the load management controller is programmed to route wind energy to that load which will be discharged soonest, also taking account of the real time price of mains electricity, the average daily duty cycle of the loads, etc.

The system of Figure 6 uses a three phase half controlled thyristor bridge to rectify the three phase output of the aerogenerator; the microcomputer performs both power coefficient optimization and load management tasks. As noted above, this arrangement desires a constant resistance load for simplest operation, and this requires that the storage heater coil and each of the water heater elements represent similar impedances ($L/R=0$). It happens that many conventional water heaters are equipped with 2-3 kW elements (240v) on tanks of most capacities (11) and storage radiators are commonly available with 3-7 kW (240v) electrical loading comprised of separate, accessible elements from 500 W- 1.5 kW. (12) This suggests that the load system of Figure 6 might be put together using commercially manufactured units and in some instances, these loads might already be present in the household which the wind power plant is to supply. Any of three loads of similar resistance value could be selected separately; the control system would see a constant resistance load. Any of these loads can be operated from either an a.c. or d.c. source, therefore they could be supplied from the mains or the aerogenerator/rectifier. The storage radiator can be matched to the water heater by an appropriate connection of the internal elements, taking care not to overheat a part of the storage block or any of the individual elements. The only equipment to be retrofitted to the existing heaters are thyristor switches, a relatively minor installation task.

4.2 COMMERCIALY AVAILABLE LOADS

4.2.1 Water Heating

As a first priority the wind energy will be stored as heat in water. The electricity council suggests an estimate of the average home consumption as 30-35 gallons per day. Hot water tanks with 50 gallon capacity are not uncommon.(11) The unit pictured in Figure 6 is typical of tanks with two immersion elements heating water in a pressurized vessel. The top element is normally connected to an unrestricted electric supply, to provide a small volume (ex. 10 gallons) charge of hot water any time of day. The lower element is often supplied through a White meter and charges the entire tank during periods when electricity is least expensive. This lower element is usually designed to heat a full tank of water (starting at 56°F) in eight hours, and the electrical loading of the immersion heater is chosen to provide this capability. As mentioned before, 1.5-3 kW are typical element ratings and the upper element is of this same order of capacity. In selecting a water heater to use as a load for the aerogenerator of Figure 6 the electrical rating of the immersion heaters must be at least great enough to load the aerogenerator running at its rated speed. Also, the storage capacity of the heater must be sufficiently large to provide all anticipated demand and to act as a sink for the aerogenerator output for a reasonable period of time during high wind activity (ex. 12 hours). The design maximum water temperature for all water heaters is in the range 140°-158°F (depending on water hardness) and the storage capacity can therefore be measured in gallons. The efficiency with which energy is stored in a water heater depends greatly on the quality of the lagging -- this should have good thermal insulation properties and be reasonably thick.

One element electric water heaters are also common and can be used as loads to sink wind energy input. This element should represent the same sort of impedance as other loads in the system, as for the dual element heater. The great disadvantage of the single element heater is that it cannot provide a quick charge of hot water at the top of the

tank and the system is therefore less flexible.

4.2.2 Storage Radiators

As a second priority, the wind energy will be stored in a conventional storage radiator as in Figure 6 . These self contained space heaters normally are supplied through a White meter and are charged by radiant electrical heating during the time of day when electricity is cheapest, the early morning hours. The stored heat is then released during the day with the output of the radiator regulated by thermostat and fan. The heat stored during the night is released so that the temperature of the airflow out of the radiator is constant and automatically controlled. A quick boost of heat can be had by manually operating a fan control. The electrical loading of the unit is typically 3-8 kW and the heaters are usually segmented, so that for example a 3 kW rated heater would have 3x1 kW embedded elements. The interior construction of the CONSTOR storage radiator is shown in Figure 7 . These heaters are intended to heat one or several adjoining rooms, but do not act as central heating for the entire home. The wide range of available electrical ratings make these storage heaters attractive partners to water heaters in the domestic wind energy utilization scheme.

There are also central heating storage units available (Centralec WF, WE, WD; Electricaire CM, CX) if whole house rather than local heating is wanted. There is a wide range of capacities available, from 38 kWh to 150 kWh (storage radiators are typically 24 kWh to 60 kWh) of heat stored in a core of solid blocks with heat exchange to air for a central warm air duct system or to water for a radiator system. The individual elements of these heaters are 1.1 kW, 2.1 kW and 2.4 kW and the terminals of these are accessible. A wind energy conversion system could be arranged with one of these central heaters as load; part of the storage core could be heated by wind power and the rest by White meter electricity. (13)

4.2.3 Auxiliary Loads

If wind energy is available at a time when the storage loads are fully charged, it is useful to have an auxiliary

sink for this energy. This could be a dumping resistor but it is more sensible to route the energy to a useful purpose. This is easiest done on a farm, where the need for heat sources are various. In the home, a radiant electric heater could be on hand for this contingency situation.

4.3. LOAD SCHEDULING

It is desirable to schedule the flow of wind generated power to the water heater and the storage radiator so as to make maximum use of the available wind energy. Water heating has been chosen as the first priority to receive wind energy, so a criterion must be established to choose which of the two immersion heating elements will dissipate the aerogenerator electrical output at any moment. The best way to determine this is to examine the daily demand cycle of a typical household for hot water and then to schedule the wind energy to provide either a long term charge on the tank or a topping charge, depending on the time of day and the present charge on the tank. The following assumptions are made about the hot water heater: 1) the lower element (LE) will heat the entire tank to 140°F from 56°F in 8 hours; 2) the upper element (UE) will heat the top gallons in the tank to 140°F in 75 minutes. The shape of the daily hot water demand pattern is based on the following assumptions (note that this is an example and is not intended to be strictly accurate for this illustrative purpose): 1) bathing is done during the evening hours 1800-2200, requiring a fully charged tank; 2) an adequate supply of hot water should always be available for wash basins at a minimum temperature of 125°F and at 140°F for meals, 0600-0800 and 1700-1900; 3) dishwashing requires hot water to be supplied from the top of the tank only; 4) laundry requires a fully charged tank several times weekly (this will be ignored for the time being). Figure 8 is a graph of the minimum allowable water temperature at each immersion element vs. time of day, according to the assumptions above. If the water temperature in the vicinity of these elements is maintained at or above these minimum levels, then an adequate supply of hot water is to be expected during the normal day defined by the assumptions. Figure 9 is a block

diagram of the load management controller which maintains the adequate supply of hot water by utilizing wind generated energy when available and mains electricity during calm periods. Since these two sources cannot be applied to any one element simultaneously, the controller operates thyristor switches to isolate them. Figure 8 is quickly interpreted: between points a-b and d-e the water temperature at the upper element is maintained at 125 F minimum to provide a supply for incidental uses. When the controller operates in upper element priority mode, any incoming wind energy is stored in the water at the top of the tank so long as the water temperature there falls between 125-140 F. If this temperature is greater than 140 F the wind energy is diverted to the lower element -- if the water tank is fully charged, the wind energy is applied to the storage heater. If UET.LT.140 F (upper element temperature less than 140 F) the controller assumes the wind energy is insufficient to maintain the nominal water temperature and the mains are applied instead. Intervals b-c and e-f show charging cycles when it is desired to charge the top part of the tank to 140 F. Segment x-y is a time period during which lower element priority is in force and energy is needed to charge the entire tank. If the water temperature at the lower element (LET) falls below the minimum prescribed by the line x-y then the mains are applied and the wind energy diverted to another load. A more complete determination of the system operating point at any time of day can be found using the flow chart, Figure 9 .

The purpose of this discussion is to point out that the demand cycle for hot water can be completely described by a set of charge times (points c,f,y) for the two immersion heaters, a nominal water temperature (125 F) and a maximum allowed temperature (140 F). The assumed demand pattern can be changed to suit the individual needs of the user, by adding, changing or deleting the charge times in Figure 8 . If for example a user desires his bathing water to be available in the morning instead of the evening then point y would be moved accordingly to an earlier hour. Likewise if the user wished to draw energy for hot water heating from

a White meter supply he would want point y. to be 0800 at the latest. During the night hours when the White meter is on, the wind energy would be diverted to the storage or auxiliary loads. Clearly the possibilities are limitless and the choice of a charge time set depends entirely on the requirements of the user. The controller acts to schedule the flow of available wind energy to that store from which it will be used first, based on the requirements of the system owner. This type of load management provides for maximum efficiency in using wind power.

4.4 ADAPTIVE CONTROL

A controller built to execute the block diagram of Figure 9 is very flexible; by changing the times at which a full or top tank charge is desired, the user can adapt the hot water supply to his individual needs. It would be best if the controller itself sensed the particular hot water demand pattern in a home, recorded this data, and adjusted its control algorithm based on this information. This adaptive controller would assume a 'typical' demand pattern represented by a default set of charge times, and would learn the actual demand pattern over a period of time in operation. This adaptation would take the form of altering the contents of two stacks of numbers, each containing charging times for one of the two immersion heaters. The object of the adaptation would be to minimize the number of instances in which the water temperature in the tank fell below the nominal value (requiring mains input) and did not quickly rise again because of high demand and insufficient supply. This algorithm remains as future work, and the task is well within the capabilities of a microcomputer, with its memory and manipulative powers. A load management controller of this sort could even take account of which days of the week the laundry was normally done!

CHAPTER FIVE

MICROPROCESSORS APPLIED TO AEROGENERATOR CONTROL

5.1 OBJECTIVE

Rapid advances in large scale integrated circuit technology in recent years have made it possible to apply digital computing capability where formerly analog techniques sufficed. Perhaps the most significant single consequence of LSI research has been the development and production of the microprocessor, a single chip monolithic integrated circuit device that contains some of the basic building blocks of a computer: arithmetic logic unit, control, and bus provisions for the addition of memory and input/output capability. The microprocessor and its essential ancillary devices make up a minimum hardware system which can be programmed and run like a computer. The performance of the designed system depends on the size and character of the microprocessor instruction set, its speed of operation, the number of binary bits in the address and data buses, the size of the memory provided, the nature of the input/output devices and other factors. For most microprocessor families, the minimum system consists of an MPU (microprocessing unit), a clock (typical frequency in MHz) a read/write or random access memory (RAM), a read only memory (ROM) and an input/output device commonly called a peripheral interface adapter (PIA). Memory space can be expanded to a maximum of 65Kx8 bit words for an 8 bit data bus machine.

The capability offered by a microprocessor based computing system (microcomputer) is suitable for process control applications such as the Imperial College wind power project. The proposal to develop a microcomputer for aerogenerator control is based on a desire to take advantage of this previously unavailable technology -- to apply new techniques to old problems. Traditionally aerogenerator controllers have been custom designed analog circuits. However many of the routines used for aerogenerator control involve the comparison of several input variables and conditional branching or switching; these are essentially

digital operations and are easily executed on a digital machine. In the past, low portability of versatile digital equipment prevented the application of digital control in wind power systems, but microprocessor digital circuits provide light, compact and mechanically simple computing capability.

For the comparison of aerogenerator control routines a microcomputer is an excellent tool; it is more versatile than other types of test equipment since its mode of operation can be varied by program changes only. An aerogenerator control microcomputer must have several general purpose analog inputs and analog and digital output channels. The machine hardware architecture design must be as general as possible, so that the computer can be adapted to a wide range of uses by writing specific programs. In its final form the aerogenerator controller circuit complexity can be reduced significantly to make it attractive for sale as part of a small scale wind energy conversion system. This configuration would be a standard one, and could be tailored to meet individual user needs by altering the control program contents to take account of the loads in the system, their priorities and the wind characteristics of the site. Although the microcomputer is a fine research instrument, its real advantages over other forms of aerogenerator controller must be realized in a saleable machine. The impetus for the application of microprocessors to the aerogenerator control task is finally an interest in developing an inexpensive, versatile and highly reliable unit as an integral part of a small scale wind energy conversion system for domestic use.

5.2 COMPARISON OF MICROPROCESSOR AND ANALOG CONTROLLERS

The flexibility and speed of a microprocessor based controller allow the evaluation of more sophisticated control routines than would be possible with an analog controller of equal cost. Analog control requires that the problem at hand be given an exact definition and that a commitment be made to the technique for solution. A microcomputer digital controller supercedes analog circuits for sophisti-

cated aerogenerator control, particularly for on-line control in a field testing situation. Since rectifier firing angle controllers or load switching controllers must be purpose built, any attempt to compare different control policies will be tedious and time consuming. The microcomputer can be programmed to act as a hill climbing or bang-bang firing angle controller with or without wind speed information, a load switching controller (three phase a.c. load supply), load management controller, data acquisition recorder, etc. Each of these duties would require the design and building of a new analog circuit. Once the basic microcomputer software is written (for restart, interrupts, etc.) the control function chosen is dependent on the ability of the programmer and the numbers of available inputs and outputs to and from the microcomputer.

The primary disadvantages to using a microcomputer controller are: 1) the temptation to ignore simple but adequate problem solutions when such a sophisticated problem solver is available; 2) the possibility that the microprocessor may become obsolete if it is not purchased from the family of a large manufacturer, since the state of the art in LSI changes rapidly. There is little danger of analog and SSI devices like diodes, resistors, gates, monostables and latches being unavailable in the future.

The cost of a marketable microcomputer aerogenerator controller is expected to be less than that for an analog controller of equal capability assuming a moderate level of control policy sophistication. As new LSI products become available and the microprocessor gives way to the monolithic microcomputer, the cost will drop further, since controller design, construction and component costs will all decrease.

5.3 CHOICE OF MICROPROCESSOR

Since the decision was taken to use a microprocessor based controller, the author had the task of choosing which microprocessor to use. The process began with a literature survey to become acquainted with the available microprocessor families, most importantly their available

devices, data word length and instruction set. The author thought an 8 bit machine to be adequate for the aerogenerator controller; microprocessors with an 8 bit data word are in common use, and although 16 bit machine families are becoming more widely used, these have more speed and arithmetic capability than is necessary for this control application. Some of the available product families are the Intel 8080, Zilog 80 (16 bit), Motorola 6800, etc.; in the end the choice came down to either the Intel or Motorola system.

The author undertook an experiment written by R. Wilde of the Computing and Control section of the Electrical Engineering department entitled "Microprocessors and Microcomputer Techniques". This involved becoming familiar with the arrangement of a Motorola MEKD2 microprocessor development kit, based on the MC6800. This experiment developed a basic knowledge of the MC6800 instruction set and the cycle of machine operation by requiring that several programs be written to perform specific duties. The MEKD2 kit is a microcomputer equipped with a hexadecimal keyboard, an LED display and software based on a monitor program. Digital to analog and analog to digital converters had been added to the basic kit and these were used in the experiment. The experience gained from several days operating the MEKD2 kit was instrumental in leading the author to choose the Motorola MC6800 family for the aerogenerator controller.

Several other contributing factors must be mentioned -- the Imperial College Computing Centre has various supportive services for microprocessor users, including an MC 6800 cross assembler. With the help of R. Wilde the author became familiar with the cross assembler and discovered the very great time savings to be realized in the writing of long instruction set programs. Several other facts influenced the author to choose the MC6800: 1) there was a body of experience with the chip in the Electrical Engineering Department; 2) advance technical information promised the appearance of a two chip 6800 compatible microcomputer which looked attractive as the final form for the controller; 3) the arrangement of the peripheral interface adapters as memory locations seemed to be a more convenient I/O provision than in some of the competing families; 4) the product

could be readily supplied by local vendors.

5.4 DESIGN OF SYSTEM ARCHITECTURE

The microcomputer architecture took its form from Figure 10 of reference 4, conceived by E. Horne of the Machines and Power group for the project proposal statement. The MC6800 system designed by the author was originally less complete than this proposal, but evolved to include most of the capabilities shown there. The MEKD2 development kit was attractive since it would have eliminated the difficulties associated with wiring and testing the core of the microcomputer. In the end the decision was made to build the system from scratch, for several reasons: 1) the MEKD2 kit cost £158 which seemed high in comparison to a system put together piece by piece; 2) the programmable read only memory (PROM) that the author wished to use (TMS 2708) was not compatible with the unmodified kit; 3) the author wished to have the experience of designing, building, testing and writing software for a microprocessor digital circuit. The personal philosophy with which the author approached this project was to put together a microprocessor system requiring the least number of devices; it became apparent that while this objective was justifiable in terms of the final form for the controller, it was not relevant to creating a research tool. As originally drawn (Figure 10) the microcomputer had no facility for the real time loading of RAM data and no display for examining the buses or the input or output levels. These were later provisions which added significantly to the cost of the microcomputer and the time necessary to put it into working order. Construction of the microcomputer began in late January 1979 and ran through June, not including time taken to design or document the work or to write the software and hill-climber control program which marks the extent of the authors' accomplishment.

It is worth examining Figure 10 to get an idea of the most important components comprising the microprocessor based controller. The heart of the system is the MC6802 microprocessor/clock/RAM. Incorporated on this chip are

the standard ALU, controls and three state bus buffers of the MC6800 and additionally 128 bytes of RAM at hex addresses £0000 to £007F and a divide by four clock circuit that requires an external crystal. A block diagram of the MC 6802 is shown in Figure 11 and further technical detail is available from Mororola Corporation and their suppliers. (14)

The programmable read only memory by Texas Instruments (TMS 2708) is a 1K x 8 device with a single enabling input. This chip was selected for the controller because there is in the Machines and Power Systems laboratory an EPROM programmer for this chip (see Appendix B). The programmer is controlled by a Nova 3 minicomputer, making use of a floppy disk program developed by Lucas Petrou as part of his Ph.D. research. Mr. Petrou also constructed a manually operable PSEUDO PROM compatible with the TMS 2708 pin-out. This unit looks to the MPU like a read-only device, but data can be entered manually through a set of toggle switches. The TMS 2708 requires a three voltage power supply which is also useful for D/A and A/D conversion. The MC6820 peripheral interface adapter is the port through which all communication with external devices takes place. This device is accessed as if it were an address in memory and it isolates bus connected devices from peripheral hardware. The incoming information about the wind energy conversion system passes through an 8 to 1 multiplexer, an A/D converter and is latched into peripheral register A (PRA) which can be read by the MPU. The peripheral register lines can be individually configured to act as either inputs or outputs and can thus be used to both select the desired input channel (with three bits configured as output) and to read the A/D result (with all of the bits set as inputs). The PIA has two peripheral registers, and PRB is configured as an output, sending data for both firing angle control and load switching. By manipulating the program controllable enable signal CB2, one or the other of these outputs can be selectively written to, eight digital (on/off) signals for load switching, or an 8 bit (resolution = 256) data word to the D/A converter. The 0. to 10 volt output of the D/A is applied to the three phase half controlled thyristor rectifier gating circuit.

The system of Figure 10 was eventually expanded to include display capability for: 1) the address bus; 2) the data bus; 3) a set of front panel switches used to load address and data in RAM; 4) a hexadecimal representation of the analog input level (data at PRA); 5) a hexadecimal representation of the firing angle output level (PRB). Another circuit was included to provide run/halt and single step provisions which are important for testing hardware and debugging programs. A block diagram of the existing controller is shown in Figure 12 and by comparing this to Figure 10 the reader can see how the architecture of the microcomputer evolved over time. A fully detailed description of the completed microcomputer circuit (Figure 13) will be found in Chapter 6, but the account above is adequate background for the chapters on software and program development (7), suggestions for future work (8), conclusions (9), and part of the appendices.

5.5 INTERFACE OF THE MICROCOMPUTER TO AN ANALOG WIND SYSTEM MODEL

The analog model of the Imperial College wind power plant created by I. Beuhring, makes use of two EAI analog computers, the TR48 and 580. Combined, these computers represent the wind rotor, aerogenerator, constant load resistance and a thyristor rectifier to control rotational speed. The single wind speed input is provided a voltage either from a potentiometer or an open reel magnetic recording of real wind data.

The hillclimbing routine of Appendix C was tested by interfacing the microcomputer to the analog model as shown in Figure 14. The connection of the microcomputer to the TR48 is straightforward, since the analog inputs will accept 0-10v input and the TR48 machine unit is 10 volts. When using the microcomputer with the analog computer, be certain that these have a common ground; the ground output from the microcomputer is the lower middle panel socket.

The hillclimbing routine was tested by interfacing the microcomputer to the TR48, varying the wind speed potentiometer (and thereby the rotational speed and power output signals) and stepping through the control program. This

strategy can be generally used to verify the operation of firing angle control policies. To operate the microcomputer as an on-line controller, the analog firing angle control signal must be disconnected from the TR48 and the 0-10v microcomputer output substituted for it.

CHAPTER 6

DETAILED MICROCOMPUTER DESCRIPTION

6.1 MOTHER BOARD

The board mounted behind the card front immediately to the left of the power supply module is the microcomputer mother board, containing the MPU, system clock, RAM, ROM and address decoding. The MC6802P is a monolithic 8-bit microprocessor that contains all the central registers and accumulators, an internal clock oscillator and driver, and 128 bytes of RAM at hex addresses £0000 to £007F. It is supplied by a +5 volt source rail that is common to the entire microcomputer. The clock crystal is a parallel cut quartz with a characteristic frequency of 3.276800 MHz. The oscillator circuit of the MC6802 divides the crystal frequency by four, so that the fundamental system clock frequency is .944200 MHz. The address bus is contained entirely on the mother board except for several PIA enabling bits (A0, A1, A12, A13), the data bus is common to several of the boards, and occupies board edge pins 29-36; Table 1 lists the edge connections for all five boards.

Starting at pin 1 and going counter clockwise, the MPU is wired thus: (1) Vss = 0 volts (2) $\overline{\text{Halt}}$: this signal originates on board no. 5, described in section 6.5 -- it is active low (3) MR: memory ready is tied hi, so that the enable signal operates in normal mode (4) $\overline{\text{IRQ}}$: this pin has four inputs, two from each of the peripheral interface adapters (IRQA and IRQB) -- these are wired-OR. A 3k Ω pullup resistor is used for optimum control of interrupts. (5) VMA: valid memory address output is used as an enable signal for both RAMs and both PIA's. (6) $\overline{\text{NMI}}$: the non-maskable interrupt is tied hi, to be inactive -- all interrupts are maskable. (7) BA: the bus available output signal is not used in the present configuration. (9-20) A0-A11: these are address bits, A0-A9 are used for PROM addressing, A0-A6 are used for RAM addressing. (21) Vss = 0 volts. (22-25) A12-A16: the top five bits of the address bus. (26-33) D0-D7: the data bus, which connects to both PROM's, both RAM's, both PIA's and an 8-bit buffered latch on board no. 4. (34) R/ $\overline{\text{W}}$: the read/write output, hi for

read, lo for write, is used as an enable for the two RAM's and two PIA's. (35)Vcc Standby: this pin supplies the d.c. voltage to the first 32 bytes of RAM as well as the RE control logic. It is presently supplied by the +5 volt rail, but if supplied from a rechargeable battery source, the lowest bytes can be saved in a power down situation. (36)RE: RAM enable, when hi enables the on-chip memory to respond to MPU controls -- tied hi. (37)E: enable or clock output, to all clocked devices. (38-39) These are the crystal input pins, which accept the parallel cut 3.276800 MHz crystal. The case of the clock crystal is grounded; if this is not done, the clock output (E) is unstable and the MPU will not function properly. (40) RESET: this active low input causes all higher order address lines to be forced high. For restart the last two locations (£FFFE, £FFFF) in memory will be used to load the program addressed by the program counter. Note that when all address lines are high, this is equivalent to £33FF, the highest address in the microcomputer memory as it is presently designed. The power supply pin to the MPU is no. 8 and it is wired to +5 volts.

Two sockets are provided to accept TMS 2708 1K x 8 programmable read only memories (PROM's). These are at addresses spaces £2000- £23FF and £3000- £33FF. PROM 0, the lowest socket on the board, is the highest block of memory space, and will always contain the RESET vector in the top two bytes. PROM 1 is optional and need only be added as PROM 0 becomes filled with program. The TMS 2708 is an N-channel silicon gate device that can store 1024 data words of 8-bit length. It requires three supply voltages, + 5 and +12. This PROM was chosen because an EPROM programmer had already been built to accept the type. The TMS 2708 has only a single enable input, requiring that there be address decoding for the PROM's. The PROM 0 enable signal is A12·A13 and that for PROM 1 is A12·A13. The PROM 0 socket is used to interface the microcomputer with a 512 x 8 PSEUDO PROM with toggle switch input, as mentioned above and described more fully in section B.2.1.

The random access memories come from the Motorola 6800 family. The MCM6810A is a 128 x 8 RAM requiring a +5 volt supply. Provision for two of these is wired on the mother

board, though both are optional; the minimum required RAM is on board the MPU device. RAM 1 is at address space £0080 - £00FF and RAM 2 is at £0100 - £017F. The chips are serviced by the lowest seven bits of the address bus and by the data bus. Each has six chip select inputs and these are as follows: RAM 1, $\overline{CS1}:A12$, $\overline{CS2}$: tied 10, $CS3:RAM1 = VMA A7$, $\overline{CS4}:A8$, $\overline{CS5}:A13$; RAM 2, $\overline{CS1}:A13$, $\overline{CS2}$: tied 10, $CS3:RAM2 = VMA A8$, $\overline{CS4}:A8$, $\overline{CS5}:A13$. Both of these devices are optional, to be added as the RAM space on board the MC6802P becomes inadequate. The remaining devices on the mother board are for RAM and PIA address decoding.

6.2 OUTPUT CONTROL BOARD

The board mounted to the card front marked 'output status', immediately left of the mother board, contains the output control circuit. The largest device on the board, nearest the connector edge, is peripheral interface adapter no. 1 (PIA 1). This is part of the 6800 family, and two such devices perform all the microcomputer input/output tasks. The MC6820P is an N-channel silicon gate integrated circuit that handles communication to and from the MPU and the microcomputer inputs and outputs. Its main features are two data direction registers (DDRA and DDRB), two peripheral registers (PRA and PRB), four I/O control lines (CA1, CA2, CB1 and CB2), and two control registers (CRA and CRB). The two peripheral registers function separately -- each is comprised of eight bits, each of which can be separately assigned as an output (logic 0 in the corresponding data direction register) or as an input (logic 1 in the corresponding DDR). When configured as inputs, these lines can be read directly by the MPU, or if outputs they may be directly written to. The PIA is accessed as four addresses in memory, one each for CRA and CRB and one each combined for DDRA/PRA and DDRB/PRB. The contents of control register bit 2 determine which of the two other registers (DDR/PR) is accessed at any time. This is understood by examining Table 2. Peripheral Register A (PRA) of PIA 1 is intended as an input and its bits are so prepared by the RESET routine (see Appendix C). These lines run to the output of an A/D converter on board

3. All analog information about the wind energy conversion system is thus entered into the microcomputer via this 8-bit port. Peripheral register B (PRB) is configured as an output, and information for both the firing angle signal and the load switching status pass through this port.

The control lines for PRA (CA1, CA2) are arranged thus: the CA1 line functions as an interrupt input and is activated on the low transition of the A/D converter STATUS signal from board 3. This indicates to the PIA that the analog input data which has been processed on board 3 is in a digital form and is ready to be read by the MPU. When the PIA detects a low going signal on CA1, bit 7 of register CRA (IRQA) is set, requesting the MPU to initiate an interrupt service routine. As mentioned above, there are four possible interrupt sources in this microcomputer, all of which are wired together at the MPU $\overline{\text{IRQ}}$ pin. There must therefore be some way for the MPU to identify the specific source of the interrupt. This is done by polling the interrupt flags in the PIA's. If CRA-7 in PIA 1 is set, indicating that the analog input information is ready, then the MPU will read the PIA control register words and test the seventh bit of each of these. When it finds one of these to be set it will clear it and service the register from which the request originated. In the case of CRA-7 in PIA 1, this bit will only be set when a piece of analog information has been converted to digital form. CB2 of PIA 1 is an enable output line for the A/D converter circuit. This signal initiates the conversion of analog data to digital form and is the most important signal to board 3. It will be discussed more fully in section 6.3. The general sequence of operation for the CA1 and CA2 bits of PIA 1 is this: CA2 is set low during program execution, thereby giving a convert command to the A/D circuit. It takes this converter some time to establish a valid digital output, and when it reaches this state it sends a negative-going signal on CA1, telling the PIA and thus the MPU that the analog input is requesting service.

The control lines for the output register PRB are arranged thus: CB1 is not used; CB2 is a program controlled enable

signal for the two output latches which are also on board 2. When CB2 goes positive to negative, this enables the load switching output latch to record information sent to PRB by the MPU. When CB2 goes negative to positive, this enables the firing angle output latch to record information sent to the PRB by the MPU. In most cases it will be desirable to change the firing angle output more frequently than the load status, and this can be managed in the following way: If the last piece of output information sent was for firing angle control and it is necessary to update this without altering the contents of the load status output latch, then the current load status must be re-written to this latch. The sequence follows: CB2 is hi after the last firing angle output write. Stored in RAM is the most recent write to the load status latch. This is written to PRB again and CB2 is made to go hi to lo, thereby writing the same data to the load status latch as was previously there. Now CB2 is in the proper state for a write from PRB to the firing angle output latch. This sequence can be followed through in similar fashion to perform two consecutive write operations to the load status output latch.

The latches mentioned in the previous paragraph are 74273 devices whose clear input is held hi; they have a single enable input which causes the data present at the input to be latched through to the output when a negative going edge is detected. Since CB2 is intended to enable these devices independently, a monostable multivibrator must be used to reverse the polarity of the CB2 signal pulse to which the load status latch is sensitive (see Figure 13) The two byte digital load status output word is displayed on the front panel of the microcomputer as a column of red LED's, each of which is lighted when the corresponding bit is logic zero; the most significant bit of the output word is at the bottom of the column. This load output word also appears at the right hand column of output plugs on the leftmost panel of the microcomputer; these outputs are either logic zero or one, corresponding to the column of red output status lamps.

The firing angle output latch is actually one of two latches that serve the same purpose -- the other is on board 5, where it records the digital firing angle output for display purposes. It was necessary to provide two latches doing the same duty because there were not enough available pins to handle data at the edge connector of board 2. For this same reason, a plug/socket set is provided to connect the load status latch outputs to the right hand column of output panel sockets on the front of the microcomputer. Care should be exercised when removing board 2 that the flexible cable carrying the load status output is not snagged. It is sufficiently long to allow board 2 to be plugged into the rack using an extender board.

The firing angle latch outputs are inputs to a free running D/A converter circuit. The analog output of this circuit is a 0-9.25 v level that is the gating signal for the bridge rectifier. Table 3 shows calibration data for this analog output, hexadecimal display number vs. output voltage. The voltage output from the microcomputer is taken from the output panel socket positioned above and between the two other columns of plugs. Digital to analog conversion is done by a ZN425E 8-bit D/A and A/D converter integrated circuit with a 741 buffer amplifier on the output. The buffer amplifier is needed to remove the offset voltage and for calibrating the converter; the calibration procedure is as follows: 1) set all bits to off (lo) and adjust the 10K pot until $V_{out} = 0.000v$; 2) set all bits to on (hi) and adjust the 22K pot until $V_{out} =$ nominal full scale reading - 1 least significant bit; 3) repeat 1 and 2. The positive supply to the buffer amplifier is +12 volts, which provides a full scale D/A output of 9.25 volts. This range should be sufficient for the bridge rectifier gating signal.

The output control board is mounted behind a two inch wide card front which holds the eight red LED's for load status indication. These are active low and each is wired with a 240Ω resistance in series between the anode and the +5 volt supply.

6.3 INPUT CONTROL BOARD

This board is mounted to the card front marked 'input control', to the left of the output control board in the rack. Its' purpose is to select one of eight analog input channels, display the channel selected by a green LED column on the card front, and to convert the chosen analog input to digital form for reading by PIA 1. The eight analog input lines run to an 8-1 CMOS analog multiplexer (MPC8S). This device directs one of the eight inputs to the A/D converter circuit. There are three channel select lines to the MPC8S and the three bit word to these is held in a quad latch (7475). The output of this latch also acts as input for a 3-8 decoder that drives the display LED's. A description of the channel write/digital data read process will explain the operation of the circuit.

During program execution, when it becomes necessary to sample one of the input channels, the following steps apply: 1) CA2, which was previously hi, goes lo, initiating the 74121 negative pulse, enabling the 74365 three state buffer and enabling the channel select latch.. By enabling the three state buffer, the A/D output bits 0, 2, and 4, which normally are inputs to PA0, PA2 and PA4 are effectively disconnected from the PIA. This is in preparation for the next step in which 2) PRA of PIA 1 is reconfigured from all of its bits being inputs to PA0, PA2 and PA4 being outputs, while PA1, PA3, PA5, PA6, PA7 remain as inputs. The three state buffer is necessary to prevent connecting the A/D output bits to the corresponding PRA bits configured as outputs. 3) A channel select digital number is written to PRA and this number is captured by the channel select latch, previously enabled by CA2 going lo. The numbers corresponding to each of the channels are listed in the software, Appendix C. 4) CA2 is made to go hi, thereby freezing the contents of the channel select latch. A short time later, the monostable multivibrator pulse finishes, putting out a positive going edge. The monostable timing components are selected to delay this positive edge occurring before the CA2 signal has been made to go hi by a standard program (see software listing). When the CA2 convert signal initially went low, the ZN425E binary counter

was reset to zero and the status output bit (input for CA1) set hi. When the positive edge of this signal is detected the counter starts to count up from zero using the MPU clock signal as input. The analog output ramps until it equals the analog voltage applied to the other input of a comparator circuit to be described presently. 6) When the inputs to the comparator are equal, the comparator output goes lo causing the status bit to go lo. This bit is input to CA1 which is configured to detect the negative edge and request interrupt service by setting the PIA interrupt output bit lo. The digital output data of the D/A, representing the hexadecimal equivalent of the analog input voltage, is read from PRA of PIA 1 by the MPU after an interrupt sort routine. The proper operation of the input control circuit depends on using the software written specifically for the purpose as listed in Appendix C. Otherwise the convert command timing may be incorrect, causing errors in data conversion.

The comparator circuit for the A/D consists of two operational amplifiers and their attendant resistors. A 741 of unity gain presents a high input impedance as seen from the analog output of the MPC8S. The resistor network in front of the non-inverting input divides analog input by a factor of four; since the A/D internal reference voltage is 2.5 v this gives a full scale analog input voltage of 0 - 10 volts, to be compatible with other equipment at Silwood Park. The 741 output is input for a 531 op amp whose high slewing rate is essential for obtaining a fast negative edge when its inputs become equal, that is when the analog output from the ZN425E is equal to one fourth of the analog input from the MPC8S. This negative edge sets the status bit low and inhibits further clock pulses to the A/D converter.

6.4 ADDRESS, DATA AND SWITCH DISPLAY BOARD

This board is mounted behind the 5x5 inch display panel and is the most difficult part of the circuit to access. It contains PIA 2 whose peripheral register bits are all set as inputs by the RESET program. These bits are hi or lo depending on the position of each of 16 switches mounted

on the display panel. The top row of these switches act as both data and address input lines, while the bottom row is for address input only. Each of these is marked with a designator label and can be traced to one of the peripheral register pins: PA0=A0, PA1=A1 ... PA7=A7, PB0=A8,D0, PB1=A9,D1 ... PB7=A15,D7. The panel switches are used for loading data to RAM during program execution for such things as initial conditions, timer settings, branch flags, etc. When PIA 2 receives an interrupt signal on CA1 (load data), CB1 (load breakpoint) or both CA1 and CB1 (load address) from the momentary push buttons on the display panel, the data present at PRA/PRB as set up on the toggle switches is read by the MPU. The load address pushbutton provides for data on the switches to be recorded in RAM, according to the $\overline{\text{IRQ}}$ routine listed in Appendix C. Thereafter, any load data requests will cause the data then set up on the panel switches to be written to the previously loaded address. A hexadecimal representation of switch positions will appear on the four display panel LED's when the rotary selector is in 'switches' position. From left to right these indicate: 1) A4-A7, 2) A0-A3 3) A12,D4-A15,D7, 4) A8,D0-A11,D3. This will seem a peculiar arrangement at first glance but it is useful when loading data to addresses £0000-£007F, the RAM space most often used. The CB2 signal for PIA 2 is used for control of the run/halt circuit of board 5 and will be discussed in section 6.5.

Also on board 4 are three 8-bit buffered latches (74412) and three tri-state buffers. The inputs to the tri-state buffers are common to the PRA/PRB inputs, that is data from the panel switches. These buffers are only on, passing input data from the switches to the hexadecimal display LED's, when enabled by the rotary selector. The hexadecimal display has 16 bits of input fed from a display bus, which connects to the outputs of various three state devices. The rotary selector enables only one source of input to the LED's at any time. Three of these sources are on board 4, the switches, address bus and data bus. The switch data runs from the display panel to the tri-state buffer inputs via a flexible cable of red miniature solid wire. Another

of the cables to board 4 is one whose blue miniature solid wires run from the display panel pushbuttons to AND gate pairs (flip-flops) that eliminate switch bounce; these signals then pass through NOR gates which encode the interrupt signals for input to CA1 and CA2 of PIA 2.

Two of the 8-bit buffered latches capture the contents of the system address bus and output this to the hex display when the rotary selector is in address position. Note that for this output the hex display is read directly from left to right so that display: 3000 = £3000 and not £0030, as it would be if the rotary selector were in 'switches' position. The third 8-bit latch captures the system data bus for display when selected by the rotary switch; in this switch position the left hand pair of LED's is blanked and the two byte data word appears on the right hand pair. The multicolored ribbon cable that plugs into board 4 carries the 16 bit display bus to the back of the display panel and thence to the hexadecimal LED's which have self contained 4-16 decoders. Also part of this cable are the three wires carrying the buffer device enable signals EA, ED, and ES (see the schematic diagram).

6.5 I/O DISPLAY, RUN/HAULT, SINGLE STEP BOARD

I/O Display: This part of the circuit works the same way as the latches and buffers on board 4. The outputs of three 74367 devices are wired into the display bus; one set of eight bits carries information about the analog input level and another eight bits handle information about the α firing angle output level. This firing angle output information passes from PRB of PIA 1 to an 8-bit latch. The enable signal for this device is a negative edge on CB2 of PIA 1 and the latch captures the same data word as an identical latch on the output control board (no. 2). The input level information comes from the digital output of the A/D converter on the input control board (no. 3). The digital representation of the input or output level can be selected for hex display by the rotary selector. The buffer enable signals are designated EI and EO on the schematic diagram, for the input and output level buffers respectively.

The run/halt and single step circuit is taken from the Motorola Microprocessor Applications manual (14) and its operation is described there. The capability to step through programs instruction by instruction is essential for debugging. The status of the MPU (run or halt) is indicated by a two color LED mounted on the card front of board 5, red for halt, green for run.

A modification made to the run/halt single step circuit allows the loading of address, data and breakpoints when the machine is halted (these functions can also be used with the MPU running). The following sequence will illustrate the circuit operation. With the machine in halt, the user presses one of three display panel pushbuttons, for example 'load address'. In addition to sending an interrupt request to PIA 2, a signal from the DPST momentary switch causes the output of a flip-flop to toggle. This flip-flop is preset by resetting the machine before a run. The toggle causes the $\overline{\text{HALT}}$ line to go hi and the MPU to run. Having received an interrupt request, the MPU jumps to the interrupt routine. An examination of the program listing will show that the first two instructions in this routine cause CB2 of PIA 2 to be set hi and the two instructions near the end of the routine (steps 01360 and 01370) cause CB2 to go lo. When CB2 goes lo, this triggers a negative pulse from a monostable multivibrator which causes the flip-flop mentioned above to toggle a second time, halting the machine. Typically one main program instruction is also executed in this sequence, so that operating any of the three 'load' pushbuttons will cause the display to show a program counter advance of one instruction. This circuit modification was designed to provide the capability for changing the contents of specific RAM addresses while stepping through a program. There is another monostable on board 5 whose output is AND connected with $\overline{\text{RESET}}$ to the J-K flip-flop preset. This device causes the J-K output to be preset whenever the machine is switched from run to halt.

The 20-way ribbon cable to board 5 carries the display bus, the enable signals EO and EI and the power supply for the display panel LED's.

6.6 POWER SUPPLY

The power supply module is fitted in the right hand side of the rack and can be easily removed. It is a modular unit manufactured by Coutant Electronics Ltd. and is designated the MPSU2. This unit supplies three voltage outputs, which are wired with common earth in this machine: +5v, -5v and +12v. The supply is designed to provide +12 and +5 volts but the output potentials can be changed, keeping in mind that current is de-rated by doing so. In changing the -12v output to -5v the nominal output current is reduced, but this is not a particular concern since -5v is used only for two PROM's and three operational amplifiers. Each of the outputs is separately fused. The +5v supply is rated at 1.5a and +12 at 0.25a. To prevent the operation of thermal foldback limiting current, the top and bottom of the rack must be clear of obstruction to allow convection cooling of the supply.

CHAPTER SEVEN

SOFTWARE AND PROGRAM DESCRIPTION

Certain segments of program are essential to the proper operation of the microcomputer hardware. A cross assembly of these segments is to be found in Appendix C. This chapter explains the need for these programs and offers supplementary information to that contained in program comment statements. This chapter should be reviewed before making use of the programs of Appendix C.

7.1 THE RESET ROUTINE (see Figure 15)

The program lines from 00400 to 00820 inclusive comprise the reset routine for the microprocessor system. A good description of the tasks accomplished by this program is found in the comment statements preceding the instruction listing. The origin address of this routine is £3000, the lowest address location in the memory block of PROM 0. In order for the MPU to initiate instruction execution at £3000 after RESET, the address locations £33FE and £33FF must contain ?£30 and ?£00 respectively (see Table 4). The RESET routine must be entered into the microcomputer memory before any use is made of the inputs and outputs, for without configuring the peripheral interface adapters, all peripheral signals remain inaccessible to the MPU. The specific addresses of the PIA control, data direction and peripheral registers are listed in Appendix C.

7.2 THE INTERRUPT ROUTINE (see Figure 16)

This program segment (00860-01740) must be included in the microcomputer memory if the user wishes to make use of the RAM load address and load data provisions, and it is essential for reading data from the analog input channels. There are four possible sources of interrupt, three caused in real time by the microcomputer operator (load data, load address, load breakpoint), and the fourth caused by a program controlled A/D conversion process. Only three of these, load data, load address and the analog input service are included in the primary program listing of Appendix C.

When the MPU $\overline{\text{IRQ}}$ input detects a logic zero state, a vector address, £3FF8,3FF9 is put out on the address bus. The two byte address formed by the combined contents of £3FF8,3FF9 is the point at which the MPU begins to execute instructions after being interrupted. Addresses £3FF8 and £3FF9 must be loaded with ?£30 and ?£46 respectively since £3046 marks the start of the interrupt sort program. Without a meaningful $\overline{\text{IRQ}}$ vector, the MPU will jump to whatever address is formed by the data at £3FF8,3FF9 and likely will enter a random loop.

The interrupt routine polls the PIA interrupt flag by testing the control word bit no. 7, the sign bit, with a branchminus instruction (BMI). If the bit is set, then the program counter will jump to the appropriate program segment to load data, load address, or read analog input. As written, the routine treats the load breakpoint signal like a false interrupt and returns the program counter to the main program. An account of the suggested load breakpoint routine can be found in section 7.5.

7.3 THE ANLG ROUTINE

The program from 01950 to 02160 is a subroutine which accomplishes the selection of one of the eight analog inputs and the initiation of its conversion to digital data. This segment outputs the necessary signals from PIA 1 for the operation of the input control board. Section 6.3 describes the design of this circuit with respect to the control signals from PIA 1; as mentioned there, the input control circuit will function properly only when subject to the subroutine ANLG, around which the timing components for the A/D convert command were chosen. By combining the information of section 6.3 with the ANLG program listing, the signal timing requirements for the input control board can be fully understood.

The main program statement immediately following the BSR ANLG instruction is WAI for the hillclimbing routine (below). The MPU, after having written the control word to CRA of PIA 1 which initiates the analog input A/D conversion, will thus wait for the conversion to be completed.

When the STATUS bit goes lo the MPU will be interrupted by PIA 1 and will jump to the $\overline{IRQ}$ routine in which it reads the newly converted digital data to RAM. It is not absolutely necessary that WAI follow BSR ANLG for hardware reasons, but if the program steps following BSR ANLG require the new value of analog input, the WAI instruction should be used.

7.4 THE HLCLMB PROGRAM

This program is not a part of the system software, but an example of the type of control program which can be implemented on the microcomputer. It aims to control the firing angle gating signal to the aerogenerator output rectifier, based on an analysis of the rotational speed of the rotor and an incremental test of the instantaneous load power. A block diagram is shown in Figure 17. This program was evaluated using the EAI TR48 analog computer model of the Imperial College wind power system. Minor problems were encountered with the memory while the program was being tested, and work ended as the available time ran out. It never operated as an on-line controller for the analog model but the next chapter suggests that this work continue since the program is sound and wants only minor debugging.

7.5 THE BKPT ROUTINE (see Figure 16)

This program was written to allow breakpoints to be inserted in the main program, points to which the MPU will run and halt. This feature would be used for long programs which might require hundreds of single step operations to reach a part of the program being tested. It is not however possible with the present hardware to cause the MPU to halt at any address in the program -- the locations of breakpoints must be prescribed and activated or not by setting a breakpoint flag. When a program is contained entirely on RAM, a monitor program can be written, for example the JBUG monitor of the MC6800 based MEKD2 kit, to load a breakpoint at any program location. The monitor reads the instruction at the requested breakpoint address and writes it to another RAM location, writing a subroutine branch instruction in its place. During program execution, the MPU comes upon

the subroutine branch and the program counter is directed to a subroutine which halts the MPU (using WAI). From this point, the operator would probably single step through part of the program. The first instruction to be executed would be that previously removed for the BSR command. It would be re-written to its previous location and the program counter would return to the main program on encountering RTS. This method of breakpoint setting requires the main program to be entered on RAM.

With the aerogenerator microcomputer, the main program is in ROM, so the MPU cannot substitute a BSR instruction at a requested breakpoint. To accomplish breakpoint operation within a ROM program several permanent steps must be written into the main program which test RAM breakpoint flags. The BKPT routine list includes an example of the sort of segment required. There are a limited, prescribed number of possible program breakpoints, whose number and location are determined by the number of these flag test segments and their locations. If there are for example flag test segments in the vicinity of addresses £3200 and £3300, and a breakpoint is requested at £3250, then the MPU can only be halted at the lower or higher location; BKPT provides the halt at the nearest breakpoint whose absolute address is lower than that of the requested breakpoint.

Breakpoint provision is unnecessary for short programs; many aerogenerator control algorithms will be short enough to single step through the entire program quite quickly. If desired the load breakpoint button can be put to other use, for instance to sequentially display the contents of the MPU accumulators and registers. This would involve writing an adequate program to add to the IRQ routine. The button interrupt circuit is in place and can be used to initiate any conceivable interrupt routine, not necessarily BKPT, although BKPT becomes indispensable as program length increases.

CHAPTER EIGHT

SUGGESTIONS FOR FUTURE APPLICATION

As the author leaves the project, the microcomputer controller has not yet been used to its full potential. The next task is to verify the operation of the hill climbing firing angle control policy. This work has been started, using the EAI TR48 analog computer, with a wind speed input signal varied by hand (a potentiometer). When the program is debugged, the microcomputer should be used for on-line control of the analog model, with a wind speed input of actual data recorded on magnetic tape. A series of tests will reveal the optimum values for the several variables, sampling frequency, α step height and cut-in wind speed. If the control policy seems to be adequate based on these tests, the program can be entered on PROM using the apparatus described in Appendix B, and the microcomputer can then be taken to Silwood Park and integrated into the system there. Since all the microcomputer inputs and outputs are 0-10 volts, the hook-up at Silwood Park should involve little more than a direct substitution of the microcomputer for the present firing angle controller. Safe in the knowledge that the controller works with the analog computer model, it can then be used for on-line control of the aerogenerator. This will prove the technical feasibility of microcomputer control, but cannot provide a meaningful comparison of the several control policies being considered.

Continuing research can be done to discover which firing angle control policy is preferred for the final form of aerogenerator controller. These tests are best done using the analog computer model, on which repeatable tests can be run using pre-recorded wind data. At present there are four hours of continuous wind data on tape -- this should be increased for doing comprehensive comparative tests among control policies. Tests can be performed in very much shorter time than the normal playback period of the wind data tape; by running a data tape of 1-3/4 ips at 15 ips, a 12 hour run can be compressed to 2 hours. This is possible for two reasons: 1) the time scaling of the analog

computer can be changed to increase the speed of all elements of the aerogenerator model; 2) the microcomputer can be operated to a much faster time base than would be used for on-line control. In all of the control policies being considered, the microcomputer controller spends most of its execution time in a delay loop so that its sampling and decision rates are meaningful with regard to the aerogenerator response time. The minimum physical time constant of the windmill is in fact so long, that the full speed capability of the microprocessor will never be used. This means that tests being run using pre-recorded wind data can be much shorter than the necessary recording time. There is therefore an opportunity to do a great many comparative control policy tests, using the same wind data each time, and to get meaningful results in a much shorter time than would be the case if all tests were done on a real system. This is the direction the author feels should be taken for firing angle control policy development.

Since the microcomputer is so light and compact, it can easily be carried to and from Silwood Park. Development and on-line testing of control policies can follow this chronology: 1) the control policy is block diagrammed, written in instruction code, cross assembled on the CDC and entered into the PSEUDO PROM, which is plugged into the PROM 1 socket. PROM 0 is a TMS 2708 containing the software necessary for basic system operation (reset, interrupt and analog input read); 2) the program is debugged by manually varying the inputs (potentiometers) to the analog model and verifying the conditional branches. For this task there is no feedback of the controller firing angle signal to the analog model, although the necessary program inputs are patched out from the analog model; 3) once the program runs, the firing angle signal can be fed back into the analog computer and tests can be run using pre-recorded wind data; 4) once model testing is finished, the newly developed control routine can be cross assembled into octal code and burned onto a PROM. The controller can then be taken to Silwood Park for on-line tests.

8.1 LOAD MANAGEMENT RESEARCH

Only preliminary programming work has been done in developing the load management control scheme of section 4.3, since most of the authors' time was spent building the microcomputer and developing software and the hill-climbing routine. The microcomputer output and input facilities needed for load switching are present in the hardware as built and programming work is all that remains to implement some form of load management. The author would suggest the following schedule for further research in this area: Write a program to provide water heating based on the block diagram of Figure 9. This routine requires three inputs -- two water temperatures and a real time clock which can be provided by applying regular pulses to the NMI input and writing a routine to count these. With a sufficiently large counter subroutine, the internal clock can even be used to derive the real time. This element priority control should be designed to allow easy expansion to adaptive control. Reducing the number of program decision variables, to for instance a table of water tank charge times, will simplify the adaptive load management policy, since this can be accomplished by changing the contents of this one table. The most important milestones of this future work are to define a criteria for making such changes and the writing of a program.

All of the testing of practical load control schemes will be done using the analog wind system model, until such time as actual loads are purchased. A part of the analog computer can be used to represent the water heating and storage heating loads as time constants, since they are charged at a predictable rate and are discharged at a rate depending on the level of use. The comprehensive wind energy conversion system model can then be brought under the control of a single unit, the microcomputer, while using taped wind speed input data.

8.2 EXPANDING THE MICROCOMPUTER FOR DATA ACQUISITION

The Motorola 6800 family of integrated circuits includes a device known as an asynchronous interface adapter (MC6850)

which performs data formatting and control to interface serial asynchronous communications information to the microcomputer bus. This device can form the heart of a circuit to read and write data to and from a cassette or other permanent external storage medium. The microcomputer capability could thus be expanded to include permanent data acquisition of such quantities as wind speed, wind direction and information about wind rotor/generator operation performance. This data can be recorded over a long period of time, limited by the capacity of the data storage medium. The format of the data would be selected to facilitate later analysis. The logic functions of the microprocessor could be used to derive and store such data as maximum and minimum wind speed per day, hour, minute, etc., or to assemble complete wind speed duration characteristics for a site. Another possibility is to program a test routine so that the microcomputer, instead of acting as an optimal controller, constructs a set of load power vs. shaft speed curves for the wind plant at various wind speeds. This method of recording would allow the site to remain unattended for the greater part of long tests. By installing a telephone/modem communicator with the data acquisition tape recorder, the site could be monitored remotely; tests could be run and data from these transmitted to the college. Test control programs could be changed and transmitted to the microcomputer. In this way the system performance would be subject to constant surveillance, not just during days that seem windy enough to warrant a trip to the site. All of the capabilities mentioned involve extensions to the microcomputer of varying complexity. A cassette recorder can be quite simply added, a remote communication system is much more clever and expensive.

As the sophistication of LSI circuitry increases, more capability becomes available in less devices. The author foresees a marketable wind energy installation controller put together from as few as a dozen IC's. The cost of producing such a circuit in moderate quantity would be small compared to the replacement cost of the energy gained from optimal control. Figure 18 is a rendering of such a unit.

CHAPTER NINE

CONCLUSIONS

The microprocessor-based aerogenerator controller is now fully operational and available for future work on various control policies. The authors' work has included the design, construction and testing of the microcomputer and the development of several control strategies to use in conjunction with the machine. This effort has led the author to believe that a microcomputer offers the best combination of low cost, high capability and flexibility possible for control of a small scale wind power system. In fact this technology is certainly applicable to larger systems as well.

The author had wished to reach the milestone of using the microcomputer for on-line control before ending work on the project but this was not possible. Sufficient time was available to assure that the microcomputer can accomplish conditional branching based on changing input variables. Some work was done with the microcomputer inputs being derived from an analog computer model of the Imperial College wind power system. A hillclimbing control policy for the firing angle signal to the aerogenerator rectifier was written and to some extent tested; the firing angle was made to decrease as load power increased, and vice-versa. No comprehensive tests using real (recorded) wind data were conducted.

In respect of the authors' personal goals the project work was successful; much was learned about the numerous design factors of wind energy conversion systems, and about the specific design of the Imperial College wind plant. A microcomputer has been provided for continuing research on aerogenerator control and household load management. In doing this the author learned the techniques for designing, wiring and testing microprocessor circuits and has become familiar with the requirements of a microcomputer system for a control application. This experience is held by the author to be one of the most valuable results of working on the aerogenerator control task.

The notion of performing microcomputer load management control for a small scale wind energy conversion system for heating domestic premises is thought to be unique. Of particular interest is the possibility of effecting adaptive control for domestic heating supply within a standard wind energy system controller. If realized, this controller would simplify the installation of a small scale wind energy plant by obviating the need to write a control program specifically for each new wind plant. The software package would provide a continuous adaptation of the home heating load scheduling, matching demand to supply while routing available wind energy to that store from which it would be extracted soonest. Chapter Four reviews a suggested method for implementing adaptive control.

The final task of this project has been to document the design and operation of the microcomputer sufficiently so that future researchers can make use of the machine. This has been a challenging job and hopefully the results will be successful.

APPENDIX A
A MICROPROCESSOR BASED CONTROLLER
FOR AN AEROGENERATOR
A SHORT OPERATING GUIDE

NOTE: Do not unplug circuit boards from the rack with the power supply on.

A researcher interested in using the aerogenerator controller microcomputer must become familiar with the Motorola 6800 instruction set. Programs cannot be written in any other form; a useful initial exercise is to go through the programs of Appendix C and come to understand their operation. An excellent general introduction to microprocessors and to the MC6800 in particular is gained by carrying out the experiment written for this purpose by R. Wilde of the Computing and Control section of the Electrical Engineering Department.

Once the microcomputer is switched on, the Reset command is given by pressing the appropriate button on the front panel. This action causes the MPU to start executing instructions at the address found in the highest two bytes of memory -- these are £33FE and £33FF in this microcomputer. For example if the contents of these addresses are £33FE = ?£10 and £33FF = ?£50 then the MPU will begin executing the program starting at £1050. The addresses £33FE and £33FF are part of the memory space assigned to PROM 0. Therefore, a ROM must be plugged into the PROM 0 socket which contains a start vector at its addresses £33FE and £33FF. The easiest way to do this short of burning a start vector into an EPROM is to use the PSEUDO PROM described in Appendix B. The operation of this machine is straightforward on examining the front panel; it is effectively a ROM (as seen by the MPU) which can be programmed by hand using the front panel toggle switches. The output cable from the PSEUDO PROM is plugged into the PROM 0 socket as described in Appendix B. When the PSEUDO PROM is properly plugged into the mother board and has been turned on, switch the LOC (local)/ COMP (compute) toggle to LOC. Then put all the address toggles (save the least significant bit) to one. Press 'load address'. Set up hex ?£00 on the toggles. Press 'load

next'. These actions have loaded £31FE and £31FF (the highest addresses in the PSEUDO PROM memory) with ?£3000. Pres LOC, turn on the microcomputer, turn the rotary selector to address, put run/halt to halt and press reset. The number 3000 should appear on the hex display and the OE light (output enable) on the PSEUDO PROM should now be lit. This indicates that the MPU is ready to read data from the PSEUDO PROM, starting at address £3000 (the lowest absolute address in the PSEUDO PROM). Now enter a short program; for instance £3000 = ?£7E, £3001 = ?£30, £3002 = ?£00. Reset. Run. The address display should show the last digit flashing as the instruction loops upon itself: JMP £3000. Programs of up to 512 words can be entered on the PSEUDO PROM and this should be sufficient space for most aerogenerator control routines. To expand the available memory capacity somewhat, burn the software program of Appendix C on to a TMS 2708 PROM and insert the device into PROM 0 socket. Use PROM 1 socket for the PSEUDO PROM, making sure that the jump to the main program from PROM 0 is to an address between £2000 and £23FF. Any difficulties in getting a program to run are almost certainly program bugs and not hardware problems. Be sure to understand the full implications of each instruction used, particularly branch tests and arithmetic operations. The author repeatedly overlooked small but important pieces of information regarding the setting of condition code register bits, with consequent waste of time.

When developing control routines for use with the analog wind power plant model, use the PSEUDO PROM as memory. Although this unit is not portable once it has been programmed (since unplugging it destroys the stored data) it is not susceptible to undesirable data changes caused by programming error. In a program entered on RAM, if a branch instruction has the wrong object byte, then there is a possibility that the MPU will go into a random loop, chewing up the memory contents. Since the MPU cannot write data to the PSEUDO PROM this cannot happen to programs entered on it. Before using the microcomputer for on-line aerogenerator control, programs should be completely

debugged, as verified on the analog model, cross assembled to octal code, burned onto a TMS 2708 PROM and tested again on the analog model. This reduces the chance of operating the windmill with a faulty control routine which might allow the rotor to cverspeed and damage itself.

A few other useful hints: Whenever the PSEUDO PROM OE light is on, the microcomputer hex data display will show the contents of the data bus (PSEUDC PROM in COMP mode) or the hex code of the PSEUDO PROM data output (LOC mode). This is useful when programming the PSEUDO PROM, since data entered on the toggle switches can be displayed in hexadecimal code and this feature aids the checking of program bytes as they are entered. The display will not show the hex code of the PSEUDO PROM data unless this machine is enabled and the MPU is halted; this condition can be entered by resetting the MPU to a start vector which points to a memory location belonging to the memory space corresponding to the socket in which the PSEUDO PROM is plugged.

The contents of the data bus are not displayed when instructions in the on-board RAM are executed. This happens because the MPU data output lines are in the off state when addresses £0000-£007F are on the address bus. All data bus communication then takes place internal to the MPU chip.

APPENDIX B

SYSTEM AIDS

B.1 THE PSEUDO PROM

This machine was originally built by L. Petrou for use with a 16 bit data bus microcomputer. The aerogenerator controller uses only eight of these data bits (D0-D7) for input to a TMS 2708 PROM socket. The pin connection of the PSEUDO PROM output plug is compatible with the TMS 2708 socket and the machine can thus be plugged in as a direct substitute for this device. The detail of the pin connection is: (1,black,A7) (2,brown,A6) (3,red A5) (4,orange,A4) (5,yellow,A3) (6,green,A2) (7,blue,A1) (8,purple,A0) (9,grey,Q1) (10,white,Q2) (11,black,Q3) (12,brown,GND) (13,red,Q4) (14,orange,Q5) (15,yellow,Q6) (16,green,Q7) (17,blue,Q8) (20,white,CS) (22,green,A9) (23,red,A8).

On the front panel of the PSEUDO PROM there are four momentary contact toggle switches; 1) load data, which loads a data word set up on the black/white toggles to the address displayed by the top row of LED's; 2) load address, which loads the address set up on the toggles, causing the data word at this address to appear on the bottom row of LED's; 3) load next, which loads the data set up on the toggles to the next address from that presently showing on the address LED's; 4) examine next, which steps one address space in the memory and displays its contents. Also on the front panel is a switch marked LOC/COMP. In the LOC position the machine cannot be read by the MPU and is safe for the changing of memory contents. In the COMP position the data outputs are ready to write to the MPU and the memory contents should not be altered. Always switch to LOC mode to make program changes. The on/off switch is taped to prevent accidental switching off of the machine, which would cause all stored data to be lost.

To load a program in the PSEUDO PROM, key in the starting address with 'load address'. Next, load the desired 8 bit data word at this address, for example to load the instruction 'branch always'(BRA), set up hex ?£20 on the toggles and press 'load data'. Then set up the next data byte, in this case the object of the branch instruction

(ex. F7) and press 'load next', and so on. Take care when using the 'load next' and 'examine next' switches that they advance the address display by only one location at a time -- both of these switches regularly skip addresses.

B.2 THE TMS 2708 EPROM PROGRAMMER

This system was designed by L. Petrou and provides for data to be stored on a non-volatile integrated circuit, the TMS 2708. This memory is arranged in 1024, 8 bit data words on an IC device which is susceptible to static damage and should be handled carefully.

B.2.1 Electrical Connections

The block diagram of Figure 19 shows the elements of the EPROM programmer system. Several electrical connections must be made before operating the NOVA 3 minicomputer. Connect a power supply of +27v to the two single wires leading from the EPROM programmer, red to +27v, green to earth. Preset the supply to +27v but do not switch on the output until ready to program the device (this procedure is described in the next section). Remove the mother board from the microcomputer rack (with the power off) and plug it back in using an extender board. Plug in the three wire lead from the PROM burner box to the PROM 0 socket (orange = +5v, black = -5v, grey = +12v). Solder the brown wire to the microcomputer earth rail (PROM 0 pin no. 12). Turn on the microcomputer. One of the PROM programmer selector LED's should light, depending on the position of the switch. Put this switch to READ. Open the back of the NOVA rack (power off) and disconnect the input and output jumper cables, one terminated by a 24 way male connector and the other by the mate female connector. Connect these to the EPROM programmer box.

B.2.2 The NOVA 3 Program: EPROM

To use the EPROM programmer start by learning to operate the NOVA 3 with the Tektronix 4010 terminal. First plug in the 4010 and assure that the local/line switch is in 'line' position. Switch on the NOVA 3 and floppy disk drive. Insert the 32K operating system floppy disk into the left hand drive, label up, then insert the disk marked 'Lucas' into

the right hand drive (label up) and close the disk drive doors. Set up the octal number 000376 on the NOVA input switches. Press the appropriate toggle switch to 'examine' thus displaying the contents of address 000376. Set up 060133 on the switches and press 'deposit', thus loading 060133 at address 000376. Set up 000377. Examine. Deposit. Set up 000376 again, then press 'reset' and 'start'. Go to the 4010 terminal and type DPl:EPROM.SV/A. This should boot up the minicomputer system and transfer control from the operating system disk by loading the EPROM disk into core memory. If this does not work, get help. The name of the file that must be accessed at DPl is EPROM. Once the NOVA 3 has accepted EPROM.SV/A, go to the NOVA panel, set up 000002, reset and start. Return to the 4010 and type INIT, thus initiating the run of the octal data base program EPROM which has five commands: 1)VERI is used to verify the contents of the EPROM in the EPROM programmer socket, for which purpose the select switch is set to 'read'. After having typed the VERI command, prompts will be returned requesting the first and last addresses of the field to be verified. These can be any octal number from zero to 2000. The INIT command has designated part of the NOVA 3 core as storage for PROM data. When VERI is executed, the NOVA compares the contents of each of its memory locations that have been assigned a PROM address, with the actual contents of these addresses on the TMS 2708. If the NOVA 3 data and PROM data do not agree, a list will be generated of each such discrepancy, location by location. For example

<u>Address</u>	<u>ROM</u>	<u>NOVA</u>
0000	0040	377
0001	0032	377
0002	0061	377
0003	0052	377

might appear, indicating that for ROM address 0, the NOVA contains the data word 377 and the actual ROM contains 0040. If no list appears then the NOVA and ROM data listings agree. Thus the contents of the ROM can be verified after being burned in by comparing the subject program in NOVA with the resulting ROM memory.

2) COPY is used to copy the contents of the ROM to the NOVA subject program space or working space. This command can be used to copy any part or all of the ROM contents to the NOVA. This is useful when the user desires to change only part of a program already on the ROM. He can copy the segments to be retained and make alterations without having to re-enter the entire program. The select switch must be in 'read' position for this command to be executed.

3)LOAD: This command facilitates the loading of octal data to the NOVA work space from the 4010 keyboard in preparation for programming the PROM. To enter data at a specific address, type the address, space, data, return; to get the NOVA to type the next address automatically, strike the return key again. When the entire program has been loaded in this manner strike CONTROL/D to escape the load command.

4)PRGM: This command transfers the data in the NOVA work space to the PROM when the select switch is in 'program' position. Programming is done by sequential address in a manner described in the TMS 2708 technical specifications. Just before executing this command two things must be done: 1) switch from 'read' to 'program' mode; 2) switch on the +27v program pulse supply, with the current limit turned all the way down.

Once the EPROM is programmed it is possible to get a hard copy of the memory contents using the teleprinter. This machine can be substituted directly for the Tektronix 4010, but the NOVA 3 clock rate must be changed (ask a knowledgeable system user to do this). After calling the program EPROM, type the VERI command with a start address of 0000 and a finishing address of 2000. Since the EPROM working space has all of its data bits logic 1 after reset, the VERI command will cause all EPROM locations to be printed except for those containing octal 377 (hex FF).

B.2.3 MC6800 Cross Assembler

There is available on the Imperial College Computing system a package which cross assembles Motorola 6800 instruction set programs to their hexadecimal machine code equivalent. This cross assembler has been used to generate the program listings of Appendix C. It is particularly

useful for assembling instruction set programs that are long or contain many conditional branching instructions. Octal output can be chosen as an option to hexadecimal, which is useful for preparing programs for entry to the EPROM programmer, since the NOVA program EPROM will accept only octal code as input. Details on the cross assembler operation are available from Program Advisory and Electrical Engineering faculty and students familiar with the MC6800 microprocessor family.

APPENDIX C

SOFTWARE AND PROGRAM LISTINGS

M68SAM IS THE PROPERTY OF MOTOROLA SPD, INC.
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MOTOROLA M6800 CROSS ASSEMBLER, RELEASE 1.2

```
00100          NAM      MICRO
00110 3000      ORG      $3000
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00115
00120 *****
00121 *THE FOLLOWING RECORD IS A LISTING OF THE SOFTWARE
00122 *PROGRAM NECESSARY FOR THE OPERATION OF THE MC6800
00123 *BASED MICROCOMPUTER, INTENDED FOR USE AS AN AERO-
00124 *GENERATOR CONTROLLER. IT CONSISTS OF THREE PARTS:
00125 *1.THE RESET ROUTINE INITIALIZES THE PERIPHERAL IN-
00126 *TERFACE ADAPTERS, THE STACK POINTER AND THE INTER-
00127 *RUPT MASK BIT; 2. THE INTERRUPT ROUTINE SORTS IN-
00128 *TERRUPT SIGNALS AND BRANCHES TO THE APPROPRIATE
00129 *PART OF MEMORY WHICH SERVICES EACH OF
00130 *THESE. THERE ARE FOUR POSSIBLE TYPES OF INTERRUPT
00131 *SIGNAL IN THE PRESENT HARDWARE CONFIGURATION AND
00132 *THESE ARE: A)LOAD ADDRESS, B)LOAD DATA (AT PRE-
00133 *VIOUSLY LOADED ADDRESS ), C)LOAD BREAKPOINT
00134 *D)IDENTIFY AND READ ANALOG INPUT. THE LOAD BREAK-
00135 *POINT PROVISION IS NOT ESSENTIAL AND IS OMITTED
00136 *FROM THIS LISTING. 3. THE SUBROUTINE WHICH ALLOWS
00137 *THE SELECTION OF AN INPUT CHANNEL IS ALSO LISTED
00138 *HERE. THESE THREE BLOCKS OF MEMORY ARE THE MINI-
00139 *MUM REQUIRED SO THAT CONTROL PROGRAMS CAN BE
00140 *TESTED. MORE DETAILED NOTES ARE INCLUDED AS PART
00141 *OF THE LISTING.
00310 *****
00320 *RESET*RESET*RESET*RESET*RESET*RESET*RESET*RESET*RES
00330 *****
00340 *INITIALIZE PIA #1
00350 *DDRA = INPUT
00355 *DDRB = OUTPUT
00360 *CA1 = 0 0
00370 *CA2 = 1 1 1 (SET EBAR HI)
00380 *CB1 = X X (DON'T CARE)
00390 *CB2 = 1 1 1 (D/A ENABLE)
00400 3000 86 38      LDA A  ?$38
00410 3002 B7 1001    STA A  $1001
00420 3005 B7 1003    STA A  $1003
00430 *$1001 = PIA #1 CRA, $1003 = PIA #1 CRB
00440 3008 86 00      LDA A  ?$00
00450 300A B7 1000    STA A  $1000
00460 300D 86 FF      LDA A  ?$FF
00470 300F B7 1002    STA A  $1002
00480 *THEREFORE $1000 IS THE INPUT REGISTER AND $1002
```

```

00481          *IS OUTPUT.
00490          *$1000 = PIA #1 DDRA/PRA, $1002 = PIA #1 DDRB/PRB
00500 3012 86 3C          LDA A  ?$3C
00510 3014 B7 1001        STA A  $1001
00520 3017 B7 1003        STA A  $1003
00530          *CLEAR INTERRUPT FLAGS IN PIA #1 BY READING
00531          *$1000 AND $1002
00540 301A B6 1000        LDA A  $1000
00550 301D B6 1002        LDA A  $1002
00560          *INITIALIZE PIA #2.
00570          *DDRA = DDRB = INPUT
00580          *CA1 = 0 1
00590          *CA2 = 1 1 0
00600          *CB1 = 0 1
00610          *CB2 = 1 1 0
00620 3020 86 31          LDA A  ?$31
00630 3022 B7 0181        STA A  $0181
00640 3025 B7 0183        STA A  $0183
00650          *$0181 = PIA #2 CRA, $0183 = PIA #2 CRB
00660 3028 86 00          LDA A  ?$00
00670 302A B7 0180        STA A  $0180
00680 302D B7 0182        STA A  $0182
00690          *THEREFORE $0180 AND $0182 ARE INPUT REGISTERS.
00700          *$0180 = PIA #2 DDRA/PRA, $0183 = PIA #2 DDRB/PRB.
00710 3030 86 35          LDA A  ?$35
00720 3032 B7 0181        STA A  $0181
00730 3035 B7 0183        STA A  $0183
00740          *CLEAR INTERRUPT FLAGS IN PIA #2 BY READING
00741          *$0180 AND $0182.
00750 3038 B6 0180        LDA A  $0180
00760 303B B6 0182        LDA A  $0182
00770          *INITIALIZE THE STACK POINTER.
00780 303E 8E 0008        LDS   ?$0008
00790          *CLEAR THE INTERRUPT MASK.
00800 3041 0E              CLI
00810          *JUMP TO THE MAIN PROGRAM.
00820 3042 7E 30F0        JMP   TOP
00830          *****
00840          *INTERRUPT*INTERRUPT*INTERRUPT*INTERRUPT*INTERRUPT*I
00850          *****
00860          *SET CB2 HI
00870 3045 86 35          LDA A  ?$35
00880 3047 B7 0183        STA A  $0183
00890          *POLL THE INTERRUPT FLAGS OF THE PIA'S TO IDENTIFY
00900          *THE SOURCE OF THE INTERRUPT REQUEST.
00910 304A B6 0181        LDA A  $0181
00920 304D 2B 0C          BMI   TEST
00930          *BREAKPOINT?
00940 304F B6 0183        LDA A  $0183
00950 3052 2B 05          BMI   IRB2
00960          *ANALOG INPUT READY?
00970 3054 B6 1001        LDA A  $1001

```

```

00980 3057 2B 4C      BMI      IRB1
00990                *FALSE INTERRUPT?
01000 3059 20 38      IRE2     BRA      HALT
01010 305B B6 0183     TEST     LDA A   $0183
01020                *LOAD ADDRESS?
01030 305E 2B 39      BMI      IRAB
01040                *NO, MUST BE DATA.
01050 3060 B6 0180      LDA A   $0180
01060 3063 B6 0182      LDA A   $0182
01070 3066 97 7D      STA A   $7D
01080                *SEND THE DATA WRITE ROUTINE TO RAM. THE ROUTINE,
01090                *WHEN WRITTEN, LOOKS LIKE THIS:
01100                *$000E LDX $7E
01110                *$0010 STX $10
01120                *$0012 LDAA $7D
01130                *$0014 STAA $---- (AT PREVIOUSLY LOADED ADDRESS) .
01140                *$0017 JMP HALT
01150 3068 86 DE      LDA A   ?$DE
01160 306A 97 0E      STA A   $0E
01170 306C 86 7E      LDA A   ?$7E
01180 306E 97 0F      STA A   $0F
01190 3070 86 DF      LDA A   ?$DF
01200 3072 97 10      STA A   $10
01210 3074 86 15      LDA A   ?$15
01220 3076 97 11      STA A   $11
01230 3078 86 96      LDA A   ?$96
01240 307A 97 12      STA A   $12
01250 307C 86 7D      LDA A   ?$7D
01260 307E 97 13      STA A   $13
01270 3080 86 B7      LDA A   ?$B7
01280 3082 97 14      STA A   $14
01290 3084 86 7E      LDA A   ?$7E
01300 3086 97 17      STA A   $17
01310 3088 86 30      LDA A   ?$30
01320 308A 97 18      STA A   $18
01330 308C 86 8F      LDA A   ?$8F
01335 308E 97 19      STA A   $19
01340 3090 7E 000E     JMP     $000E
01350                *RETURN FROM INTERRUPT
01360 3093 86 2D      HALT     LDA A   ?$2D
01370 3095 B7 0183     STA A   $0183
01380 3098 3B          RTI
01390                *FOR AN EXPLANATION OF STEP 01360 SEE THE
01395                *SOFTWARE DESCRIPTION.
01400                *ADDRESS READ/WRITE ROUTINE:
01410 3099 B6 0180     IRAB     LDA A   $0180
01420 309C F6 0182      LDA B   $0182
01430 309F 97 7E      STA A   $7E
01440 30A1 D7 7F      STA B   $7F
01450 30A3 20 EE      BRA      HALT
01460                *ANALOG INPUT IS READY: READ TO MEMORY
01470                *DECODE THE INDEXED ADDRESS AT WHICH TO STORE THE

```



```

01471      *NEW ANALOG DATA
01480 30A5 7F 0053 IRB1 CLR $0053
01490 30A8 7F 0054      CLR $0054
01500      *STORE THE RTI STACK POINTER AT $79,7A.
01510 30AB 9F 79      STS $79
01520      *LDS WITH TOP OF CHANNEL SELECTED STACK.
01530 30AD 8E 01BF      LDS ?$01BF
01540      *PULL THE ELEMENTS OUT OF THIS STACK IN TURN,
01550      *TESTING TO SEE WHICH CHANNEL THE ANALOG DATA
01551      *HAS COME FROM.
01560 30B0 32      PA PUL A
01570 30B1 91 6A      CMP A $6A
01580 30B3 27 05      BEQ OUT
01590 30B5 7C 0054      INC $0054
01600 30B8 20 F6      BRA PA
01610      *STORE THE ANALOG DATA
01620 30BA DE 53      OUT LDX $53
01630 30BC B6 1000      LDA A $1000
01640 30BF A7 6B      STA A $6B,X
01650      *DISABLE THE INTERRUPT INPUT CA1 ON PIA #2 -- IT IS
01660      *ENABLED BY THE SUBROUTINE ANLG WHICH SELECTS THE
01665      *ANALOG INPUT CHANNEL.
01670 30C1 86 3C      LDA A ?$3C
01680 30C3 B7 1001      STA A $1001
01690      *CLEAR THE INTERRUPT BIT CA1.
01700 30C6 B6 1001      LDA A $1001
01710      *RELOAD THE PROGRAM STACK POINTER.
01720 30C9 9E 79      LDS $79
01730      *RETURN FROM THE INTERRUPT ROUTINE.
01740 30CB 3B      RTI
01750      *~~~~~*
01751      *ANLG*ANLG*ANLG*ANLG*ANLG*ANLG*ANLG*ANLG*ANLG*ANLG*
01755      *~~~~~*
01760      *THE NEXT LISTED SEGMENT IS THE SUBROUTINE ANALG,
01761      *WHICH SELECTS THE ANALOG INPUT CHANNEL TO BE READ.
01762      *THE OPERATIONAL DESCRIPTION OF THE INPUT CONTROL
01763      *CIRCUIT SHOULD BE READ SO AS TO FULLY UNDERSTAND
01764      *THIS PROGRAM SEGMENT. THE STEPS IN THE MAIN PRO-
01765      *GRAM WHICH MUST IMMEDIATELY PRECEDE THE CALLING
01767      *OF THIS SUBROUTINE ARE:
01768      * LDA ?$XX
01769      *WHERE XX IS THE CHANNEL DESIGNATOR, ONE OF EIGHT.
01770      *THESE ARE AS FOLLOWS, STARTING WITH THAT DESIGNA-
01771      *TOR WHICH SELECTS THE INPUT CHANNEL WHOSE PANEL
01772      *SOCKET IS ON THE TOP OF THE LEFT HAND COLUMN OF
01773      *SOCKETS MOUNTED IN THE LEFTMOST CARDFRONT ON THE
01774      *MICROCOMPUTER, AND WORKING DOWNWARD: 15,14,11,10,
01775      *05,04,01,00.
01776      *STAA $6A
01777      *NOTE THAT $6A IS THE LOCATION OF THE ANALOG INPUT
01778      *CHANNEL SELECT BYTES.
01779      *BSR ANLG

```

```

01915 *****
01920 *NOW FOLLOWS THE SUBROUTINE LISTING:
01930 *
01940 *CLEAR EBAR
01950 30CC 86 30 ANLG LDA A ?$30
01960 30CE B7 1001 STA A $1001
01970 *SET PA0,PA2,PA4 AS OUTPUTS.
01980 30D1 86 15 LDA A ?$15
01990 30D3 B7 1000 STA A $1000
02000 *ACCESS PRA
02010 30D6 86 34 LDA A ?$34
02020 30D8 B7 1001 STA A $1001
02030 *SELECT CHANNEL
02040 30DB 96 6A LDA A $6A
02050 30DD B7 1000 STA A $1000
02060 *EBAR SET, CA1 ACTIVE ON LOW TRANSITION, ACCESS DDRA
02070 30E0 86 39 LDA A ?$39
02080 30E2 B7 1001 STA A $1001
02090 *SET ALL BITS OF PRA AS INPUT.
02100 30E5 86 00 LDA A ?$00
02110 30E7 B7 1000 STA A $1000
02120 *ACCESS PRA
02130 30EA 86 3D LDA A ?$3D
02140 30EC B7 1001 STA A $1001
02150 *RETURN FROM SUBROUTINE.
02160 30EF 39 RTS
02170 *THE INSTRUCTION WHICH MUST IMMEDIATELY FOLLOW
02171 *BSR ANLG IN THE MAIN PROGRAM IS: WAI
02190 *
02200 *THE MAIN PROGRAM WRITES THE DESIRED INPUT CHANNEL
02201 *TO BE SAMPLED. THEN THE SUBROUTINE ABOVE IS CALLED,
02202 *DURING WHICH THE INPUT IS SELECTED AND THE D/A
02203 *CONVERSION STARTED. THE SUBROUTINE ENDS AND A
02204 *WAIT FOR INTERRUPT INSTRUCTION IS ENCOUNTERED
02205 *IN THE MAIN PROGRAM. WHEN THE STATUS BIT FROM
02206 *THE D/A GOES LOW, CA1 WILL SET IRQA AND THE IN-
02207 *PUT DATA WILL BE READ AND WRITTEN TO A RAM LOCA-
02208 *TION CORRESPONDING TO THE APPROPRIATE INPUT
02209 *CHANNEL, BY THE ANALOG BRANCH OF THE ROUTINE
02210 *ABOVE.
02290 *****
02295 *HLCLMB*HLCLMB*HLCLMB*HLCLMB*HLCLMB*HLCLMB*HLCLMB*HL
02300 *****
02400 *THE NEXT PROGRAM SEGMENT IS THE HILLCLIMBER ROUTINE
02401 *FOR AEROGENERATOR CONTROL. THE OPERATION OF THIS
02402 *PROGRAM CAN BE UNDERSTOOD BY EXAMINING THE APPRO-
02403 *PRIATE FLOW CHART. A SHORT SUMMARY: THE PROGRAM
02404 *EXAMINES TWO CHRONOLOGICAL SAMPLES OF THE LOAD
02405 *POWER EXTRACTED FROM AN AEROGENERATOR. THESE ARE
02406 *SEPARATED IN TIME BY DELTA T. THE DIFFERENCE BE-
02407 *TWEEN THESE TWO IS USED TO DETERMINE A MAGNITUDE
02408 *ADJUSTMENT FOR ALPHA, THE GATING SIGNAL TO A

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02409      *THREE PHASE HALF CONTROLLED THYRISTOR RECTIFIER
02410      *WHICH APPEARS BETWEEN THE OUTPUT TERMINALS OF
02411      *THE AEROGENERATOR AND THE CONSTANT RESISTANCE LOAD.
02500      *
02510      *SAMPLE THE SHAFT ROTATIONAL SPEED OMEGA.
02520 30F0 86 01 TOP    LDA A  ?$01
02530 30F2 97 6A      STA A  $6A
02540 30F4 BD 30CC      JSR    ANLG
02550 30F7 3E          WAI
02560      *TEST TO SEE IF THE ROTATIONAL SPEED OF THE
02570      *GENERATOR IS GREATER THAN A MINIMUM VALUE,
02580      *ABOVE WHICH WE DESIRE TO APPLY LOAD.
02590 30F8 96 6C          LDA A  $6C
02600 30FA C6 00          LDA B  ?$00
02610 30FC 90 62          SUB A  $62
02620 30FE C2 00          SBC B  ?$00
02630 3100 2A 09          BPL    START
02640      *OMEGA.LT.OMEGA MIN THEREFORE SET ALPHA = 180 DEGREE
02650 3102 86 FF 180    LDA A  ?$FF
02660 3104 97 60          STA A  $60
02670 3106 BD 3162      JSR    ALP
02680 3109 20 E5          BRA    TOP
02690      *THE ROTATIONAL SPEED IS SUFFICIENT TO BEGIN LOADING
02700      *THE MACHINE. SEND THE INITIAL CONDITION VALUE
02701      *OF ALPHA.
02710 310B 96 63 START  LDA A  $63
02720 310D 97 60          STA A  $60
02730 310F BD 3162      JSR    ALP
02740      *SEND THE INITIAL CONDITION LOAD POWER.
02750 3112 96 64          LDA A  $64
02760 3114 97 5C          STA A  $5C
02770      *SET P2 =P1:
02780 3116 96 5C CONT   LDA A  $5C
02790 3118 97 5B          STA A  $5B
02800      *READ THE NEW VALUE OF THE REAL TIME LOAD POWER, P0.
02810 311A 86 15          LDA A  ?$15
02820 311C 97 6A          STA A  $6A
02830 311E BD 30CC      JSR    ANLG
02840 3121 3E          WAI
02850      *SET P1 = P0.
02860 3122 96 72          LDA A  $72
02870 3124 97 5C          STA A  $5C
02880      *P2 - P1 = ?
02890 3126 96 5B          LDA A  $5B
02900 3128 C6 00          LDA B  ?$00
02910 312A 90 5C          SUB A  $5C
02920 312C C2 00          SBC B  ?$00
02930 312E 27 42          BEQ    DELAY
02940 3130 2A 1A          BPL    PLUS
02950      *P2 - P1 < 0, THEREFORE ADJUST THE PRESENT VALUE
02960      *ALPHA TO ALPHA = ALPHA - DELTA ALPHA.
02970 3132 96 60          LDA A  $60

```

```

02980 3134 C6 00      LDA B  7$00
02990 3136 90 65      SUB A  $65
03000 3138 C2 00      SBC B  7$00
03010 313A 2A 06      BPL     STORE
03020                *ALPHA < 0, THEREFORE ASSIGN ALPHA = 0.
03030 313C 86 00      LDA A  7$00
03040 313E 97 60      STA A  $60
03050 3140 20 02      BRA     SEND
03060 3142 97 60      STORE STA A  $60
03070 3144 BD 3162    SEND JSR     ALP
03080 3147 BD 3172    JSR     DELAY
03090 314A 20 CA      BRA     CONT
03100                *P2 -P1 > 0, THEREFORE ADJUST THE PRESENT VALUE
03110                *OF ALPHA TO ALPHA =ALPHA + DELTA ALPHA.
03120 314C 96 60      PLUS  LDA A  $60
03130 314E C6 00      LDA B  7$00
03140 3150 9B 65      ADD A  $65
03150 3152 90 66      SUB A  $66
03160 3154 C2 00      SBC B  7$00
03170 3156 2A AA      BPL     I80
03180                *ALPHA, LE. ALPHA MAX THEREFORE CONTINUE:
03190 3158 97 60      STA A  $60
03200 315A BD 3162    JSR     ALP
03210 315D BD 3172    JSR     DELAY
03220 3160 20 B4      BRA     CONT
03230                *****
03240                *ALP*ALP*ALP*ALP*ALP*ALP*ALP*ALP*ALP*ALP*ALP*ALP*ALP
03250                *****
03260                *THIS SUBROUTINE WRITES THE ALPHA OUTPUT:
03270 3162 96 60      ALP   LDA A  $60
03280 3164 B7 1002    STA A  $1002
03290 3167 86 34      LDA A  7$34
03300 3169 B7 1003    STA A  $1003
03310 316C 86 3C      LDA A  7$3C
03320 316E B7 1003    STA A  $1003
03330 3171 39          RTS
03340                *****
03350                *DELAY*DELAY*DELAY*DELA*DELAY*DELAY*DELAY*DELAY*DELA
03360                *****
03370                *THIS SUBROUTINE PROVIDES THE DELAY TIME DELTA T.
03380 3172 96 67      DELAY LDA A  $67
03390 3174 97 58      STA A  $58
03400 3176 7A 0058    HI1   DEC     $58
03410 3179 27 14      BEQ     RET
03420 317B 96 68      LDA A  $68
03430 317D 97 59      STA A  $59
03440 317F 7A 0059    HI2   DEC     $59
03450 3182 27 F2      BEQ     HI1
03460 3184 96 69      LDA A  $69
03470 3186 97 5A      STA A  $5A
03480 3188 7A 005A    HI3   DEC     $5A
03490 318B 27 F2      BEQ     HI2

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03500 318D 20 F9      BRA    HI3
03510 318F 39      RET    RTS
03520      ****
03530      ****
03540      *THE FOLLOWING STACK OF EIGHT NUMBERS MUST
03550      *BE SET UP AT THE ADDRESSES LISTED, AS THE
03560      *CHANNEL SELECTED STACK (SEE STEP #01530).
03570      *$01A0  00
03580      *$01A1  01
03590      *$01A2  04
03600      *$01A3  05
03610      *$01A4  10
03620      *$01A5  11
03630      *$01A6  14
03640      *$01A7  15
03650      ****
03660      ****
03670      *****
03680      END

```

SYMBOL TABLE

IRB2	3059	TEST	305B	HALT	3093	IRAB	3099	IRB1	30A5
PA	30B0	OUT	30BA	ANLG	30CC	TOP	30F0	I80	3102
START	310B	CONT	3116	STORE	3142	SEND	3144	PLUS	314C
ALP	3162	DELAY	3172	HI1	3176	HI2	317F	HI3	3188
RET	318F								

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MOTOROLA M6800 CROSS ASSEMBLER, RELEASE 1.2

01250				NAM	BKPT
00050				ORG	\$0000
00060	0000				
00070				*****	
00080				♦BKPT♦BKPT♦BKPT♦BKPT♦BKPT♦BKPT♦BKPT♦BKPT♦BKPT♦BKPT♦E	
00090				*****	
00100				♦THE ROUTINE LISTED BELOW INSERTS BREAKPOINTS	
00110				♦INTO A ROM LOADED PROGRAM WHEN THE APPROPRI-	
00120				♦ATE STEPS ARE PRESENT IN THE MAIN PROGRAM.	
00130				♦IT IS NOT LISTED AS PART OF THE ESSENTIAL	
00140				♦MICROCOMPUTER SOFTWARE BECAUSE THERE WAS IN-	
00150				♦SUFFICIENT MEMORY SPACE IN THE BOX FROM TO	
00160				♦TEST THE BREAKPOINT PROGRAM AS PART OF THE	
00170				♦INTERRUPT SERVICE PROGRAM SEGMENT, OF WHICH	
00180				♦IT SHOULD BE A PART. IT WOULD OPERATE AS	
00190				♦DESCRIBED IN CHAPTER 7:SOFTWARE DESCRIPTION.	
00200				*****	
00210	0000	B6	0180	LDA A	\$0180
00220	0003	F6	0182	LDA B	\$0182
00230	0006	97	7B	STA A	\$7B
00240	0008	97	7C	STA A	\$7C
00250				♦LOAD FLAG VECTOR	
00260	000A	86	00	LDA A	?\$00
00270	000C	97	76	STA A	\$76
00280				♦STORE RTI STACK POINTER.	
00290	000E	9F	79	STS	\$79
00300				♦COMPARE BREAKPOINT FROM SWITCHES	
00310				♦TO PRESCRIBED MAXIMUM BREAKPOINT	
00320	0010	96	96	LDA A	ZZ
00330	0012	90	7C	SUB A	\$7C
00340	0014	25	0A	BCS	BB
00350	0016	96	98	LDA A	YY
00360	001A	90	7B	AA	SUB A \$7B
00370	001C	24	08		BCC CC
00380	001E	20	7A		BRA HALT
00390	0020	96	98	BB	LDA A YY
00400	0022	4A			DEC A
00410	0023	20	F5		BRA AA
00420				♦LOAD STACK POINTER WITH ADDRESS - 1	
00430				♦OF TOP OF OBJECT BREAKPOINT STACK	
00440				♦WRITTEN IN ROM	
00450	0026	8E	0000	CC	LDS ?\$0000
00460				♦NOTE THIS INSTRUCTION CONTAINS THE	
00470				♦DUMMY ADDRESS \$0000 FOR ASSEMBLY PURPOSES.	

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00480 0029 32      PULA    PUL A
00490 002A 33      PUL B
00500 002B 97 77    STA A   $77
00510 002D D7 78    STA B   $78
00520              *PERFORM DOUBLE PRECISION SUBTRACTION
00530              *TO IDENTIFY WHICH PRESCRIBED BREAK-
00540              *POINT IS CLOSEST TO (LESS THAN IN
00550              *ABSOLUTE ADDRESS) THE BREAKPOINT
00560              *READ FROM THE SWITCHES.
00570 002F 96 7C    LDA A   $7C
00580 0031 90 78    SUB A   $78
00590 0033 25 08    BCS     EE
00600 0035 96 7B    LDA A   $7B
00610 0037 90 77    DD      SUB A   $77
00620 0039 25 0C    BCS     FLGST
00630 003B 20 05    BRA     NEXT
00640 003D 96 7B    EE      LDA A   $7B
00650 003F 4A      DEC A
00660 0040 20 F5    BRA     DD
00670 0042 7C 0076 NEXT INC     $76
00680 0045 20 E2    BRA     PULA
00690              *THE PROPER BREAKPOINT HAS BEEN
00700              *IDENTIFIED. SET THE APPROPRIATE FLAG.
00710 0047 CE 0000 FLGST LDX     ?$0000
00720 004A 9C 75    CPX     $75
00730 004C 27 03    BEQ     LDA
00740 004E 08      INX
00750 004F 20 AF    BRA     ?$F9
00760 0051 86 00    LDA     LDA A   ?$00
00770              *NOTE THAT THE FLAG FIELD STARTS AT $0011.
00780 0053 A7 10    STA A   $10,X
00790              *RELOAD THE STACK POINTER.
00800 0055 9E 79    LDS     $79
00810 0057 86 2D    LDA A   ?$2D
00820 0059 B7 0183 STA A   $0183
00830 005C 3B      RTI
00840              *
00850              *SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*SWI*
00860              *
00870              *THIS ROUTINE IS THE OBJECT OF THE
00880              *SWI POINTER FFFA,FFFB.
00890              *STORE THE RTI STACK POINTER
00900 005D 9F 79    STS     $79
00910              *ADJUST STACK POINTER TO YIELD ABSOLUTE
00920              *ADDRESS AT WHICH SWI TOOK PLACE.
00930 005F 31      INS
00940 0060 31      INS
00950 0061 31      INS
00960 0062 31      INS
00970 0063 31      INS
00980              *PULL THE ABSOLUTE ADDRESS OF THE
00990              *SWI COMMAND AND LDX WITH IT.

```

```

01000 0064 32          PUL A
01010 0065 33          PUL B
01020 0066 97 77       STA A $77
01030 0068 D7 78       STA B $78
01040 006A DE 77       LDX $77
01050                  *LOAD THE FLAG CLEAR VECTOR.
01060 006C 86 00       LDA A ?$00
01070 006E 97 76       STA A $76
01080                  *FIND OUT WHICH BREAKPOINT IS SET.
01090 0070 9E 00       LDS $0000
01100                  *THIS DUMMY ADDRESS MARKS THE TOP OF
01110                  *THE OBJECT BREAKPOINT STACK.
01120 0072 32          AB PUL A
01130 0073 33          PUL B
01140 0074 97 77       STA A $77
01150 0076 D7 78       STA B $78
01160 0078 9C 77       CPX $77
01170 007A 27 05       BEQ FLGCLR
01180 007C 7C 0076     INC $76
01190 007F 20 F1       BRA AB
01200                  *CLEAR THE BREAKPOINT FLAG.
01210 0081 CE 0000     FLGCLR LDX ?$0000
01220 0084 9C 75       CPX CPX $75
01230 0086 27 02       BEQ LDA
01240 0088 20 FA       BRA CPX

01250 0051 86 01       LDA LDA A ?$01
01260 0053 A7 11       STA A $11,X
01270                  *RELOAD THE RTI STACK POINTER.
01280 0055 9E 79       LDS $79
01290                  *RTI
01300 0057 86 2D       LDA A ?$2D
01310 0059 B7 0183     STA A $0183
01320 005C 3B         RTI
01330                  ******
01340                  *THE BREAKPOINT PROGRAM THAT
01350                  *APPEARS IN THE MAIN PROGRAM MUST
01360                  *TAKE THE FOLLOWING FORM:
01370                  *
01380                  *1ST BREAKPOINT:
01390                  *
01400                  * LDA $11
01410                  * BGT ?$02
01420                  * SWI
01430                  * WAI
01440                  *CONTINUE.....
01450                  *
01460                  *2ND BREAKPOINT:
01470                  *
01480                  * LDA $12
01490                  * BGT ?$02
01500                  * SWI

```



```

01510      ♦ WAI
01520      ♦CONTINUE.....
01530      ♦ETC.
01540      ♦THE BREAKPOINT STACK WILL LOOK LIKE THIS:
01550      ♦ $0001 BPH
01560      ♦ $0002 BPL
01570      ♦ $0003 BPH
01580      ♦ $0004 BPL
01590      ♦ETC. (NOTE THAT THESE ARE HYPOTHETICAL
01600      ♦ADDRESSES)
01610 005D 0002  ZZ      RMB      2
01620 005F 0002  YY      RMB      2
01625 0061 0002  HALT    RMB      2
01630      ♦ZZ AND YY ARE THE REQUESTED BREAKPOINT BYTES.
01640      END

```

SYMBOL TABLE

AA	001A	BB	0020	CC	0026	PULA	0029	DD	0037
EE	003D	NEXT	0042	FLGST	0047	LDA	0051	AB	0072
FLGCLR	0081	CPX	0084	ZZ	0096	YY	0098	HALT	009A

/BYE

```

UMEEE26  LDG OFF.  16.16.16:
UMEEE26  CP       13.760 SEC.

```

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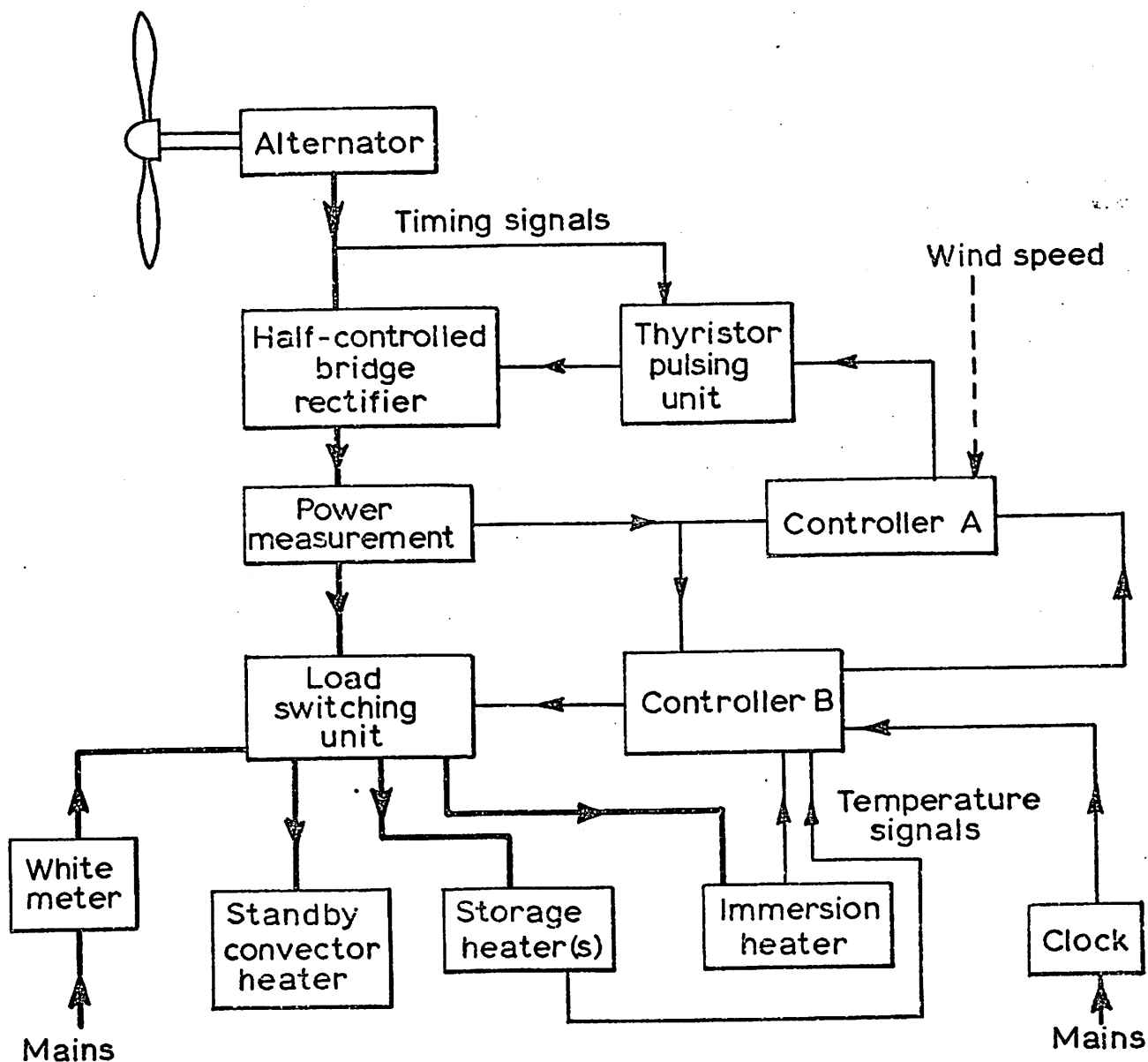


Figure 1. Block diagram of the Imperial College wind power system -- performance optimized scheme.

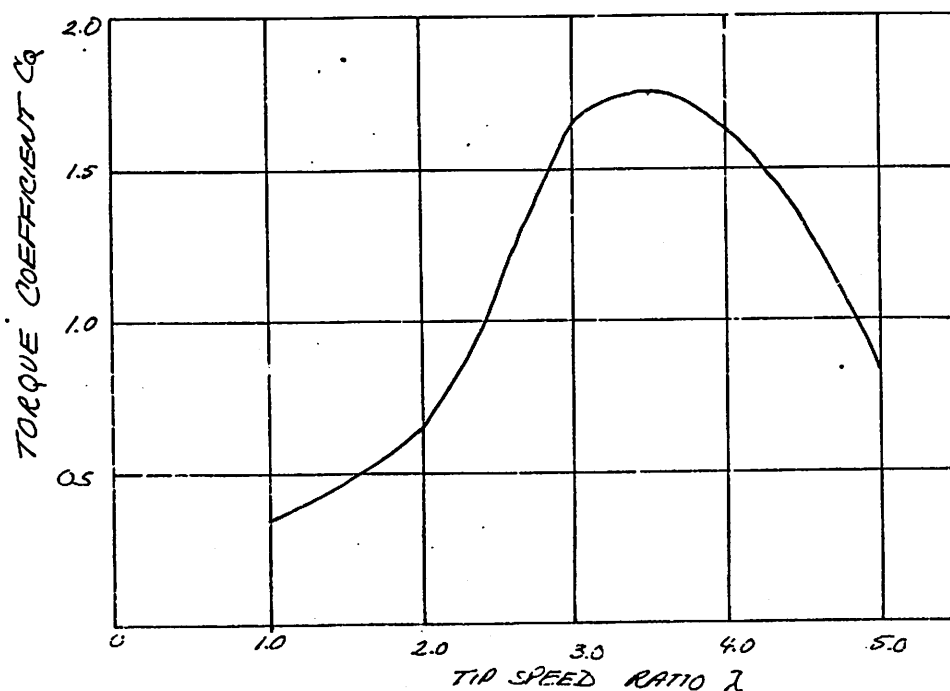


FIGURE 2. TORQUE COEFFICIENT vs. TIP SPEED RATIO FOR ARCHED PLATE ROTOR BLADES.

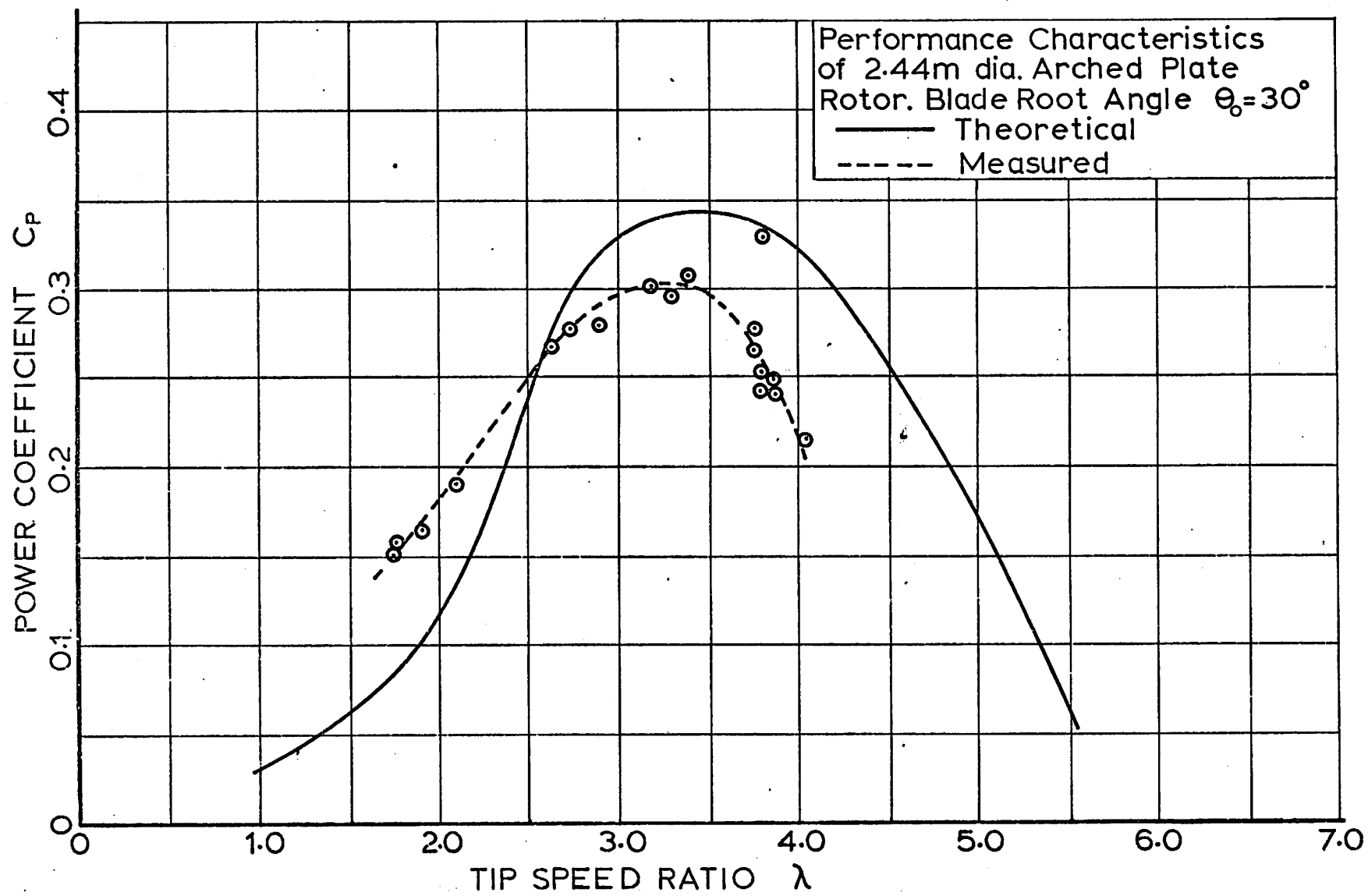


Figure 3.

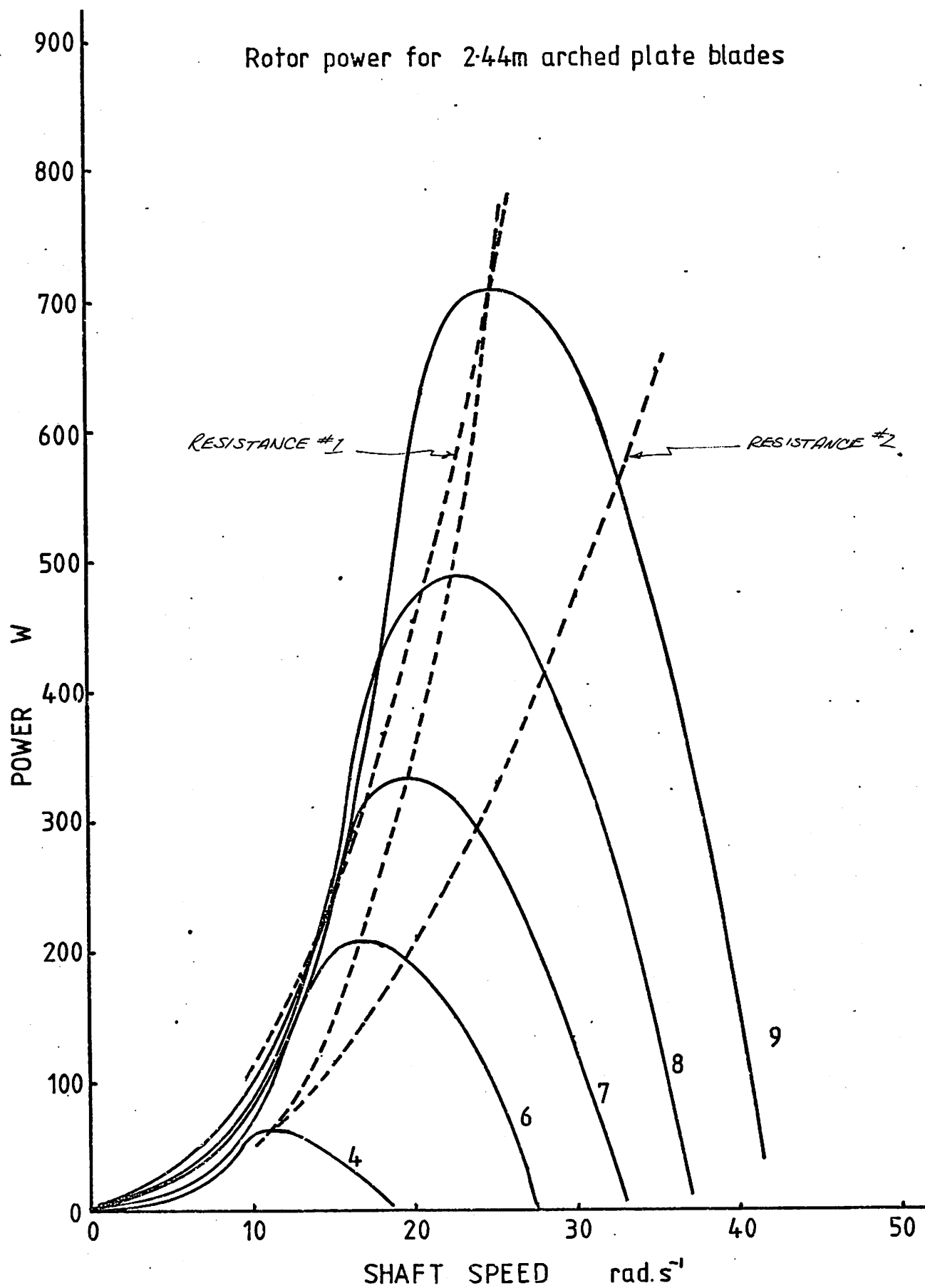


FIGURE 4.

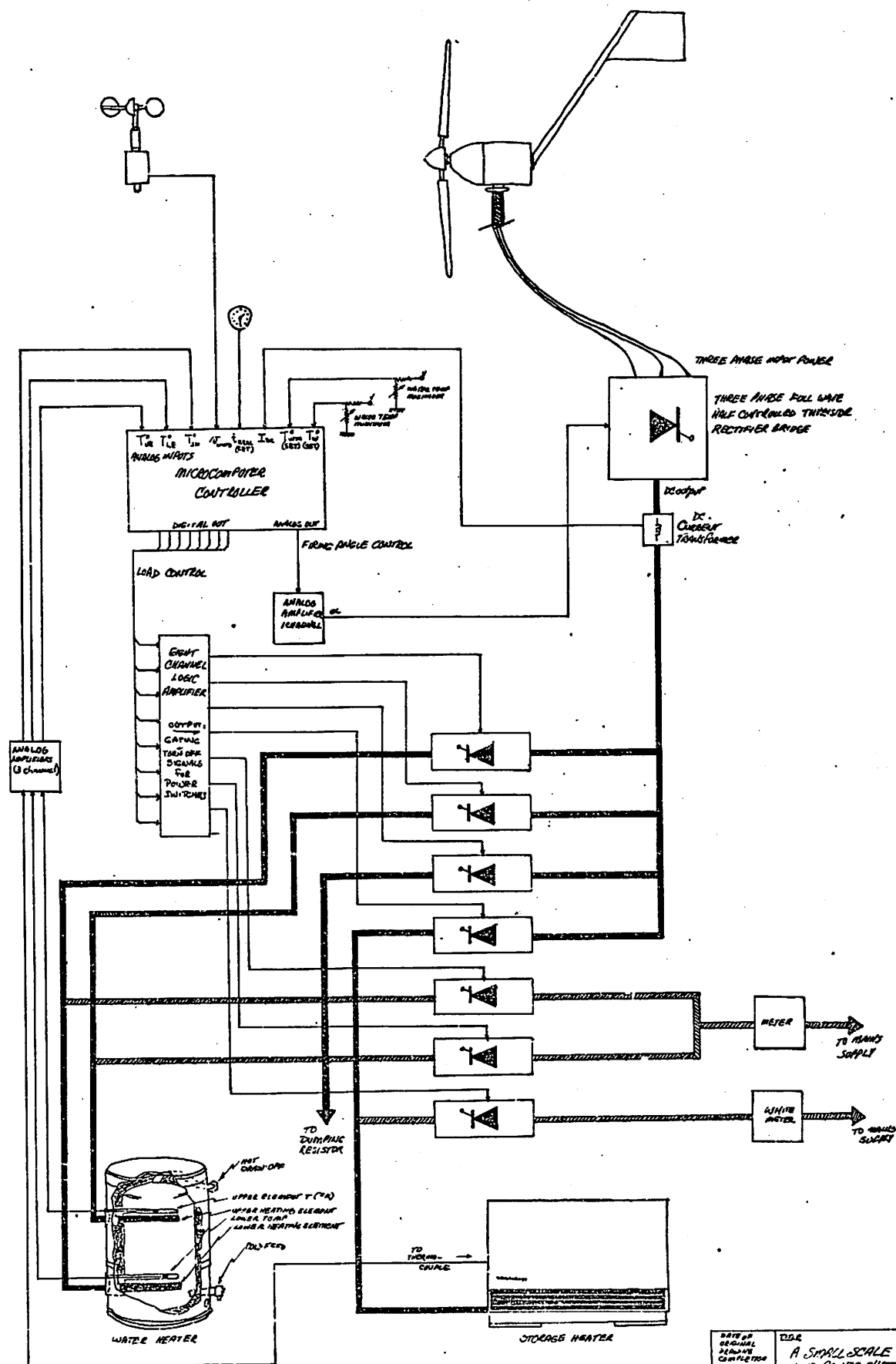
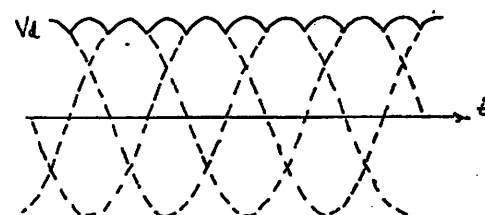
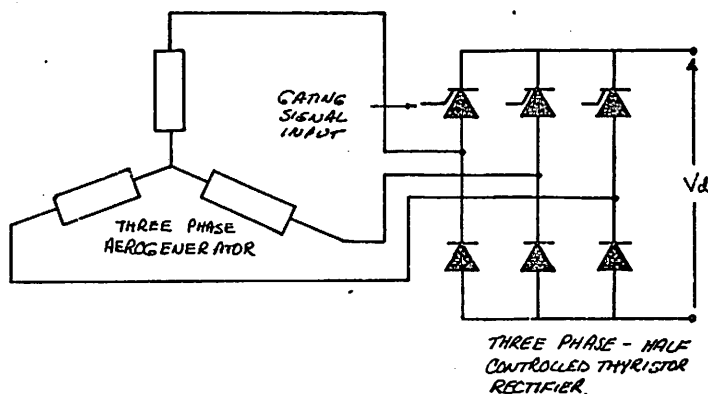


FIGURE 6.

DATE OF ORIGINAL DESIGN COMPLETED JAN 4 1979	DDR A SMALL SCALE WIND POWER SYSTEM FOR HEATING DOMESTIC PREMISES
DESIGNED BY J. HALL	EMPEROR COURSE OF DESIGN - TECHNOLOGY LONDON



VOLTAGE WAVEFORM FOR THREE PHASE - HALF CONTROLLED BRIDGE @ $\alpha = 0^\circ$.

Figure 5. THREE PHASE HALF CONTROLLED THYRISTOR BRIDGE FOR RECTIFYING THE OUTPUT OF AN AEROGENERATOR

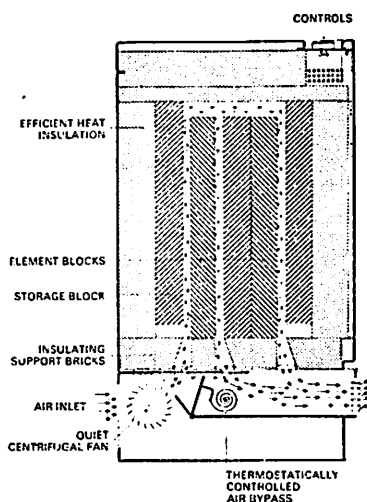


Figure 7. Cross section of a CONSTOR storage radiator.

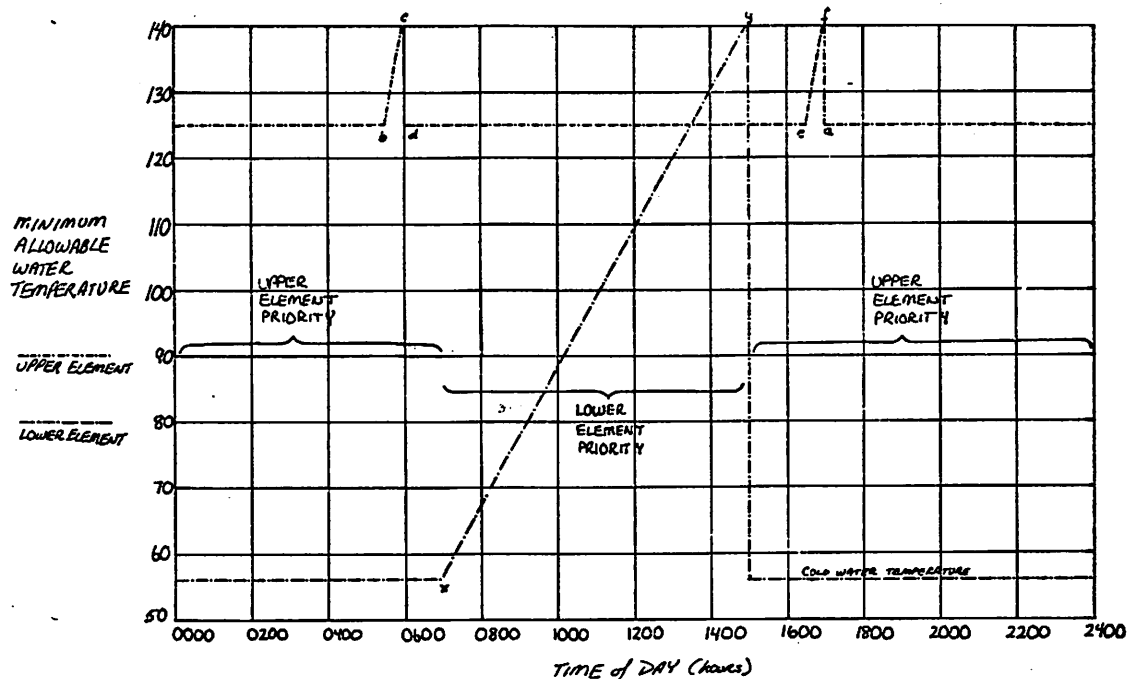


FIGURE 8. SAMPLE PLOT OF MINIMUM ALLOWABLE WATER TEMPERATURE AT THE LOWER AND UPPER IMMERSION HEATED ELEMENTS OF A STANDARD HOT WATER TANK. THESE BOUNDARIES ARE CRITERIA FOR LOAD MANAGEMENT CONTROL IN A WIND ENERGY CONVERSION SYSTEM (SEE TEXT AND FIG. 9.)

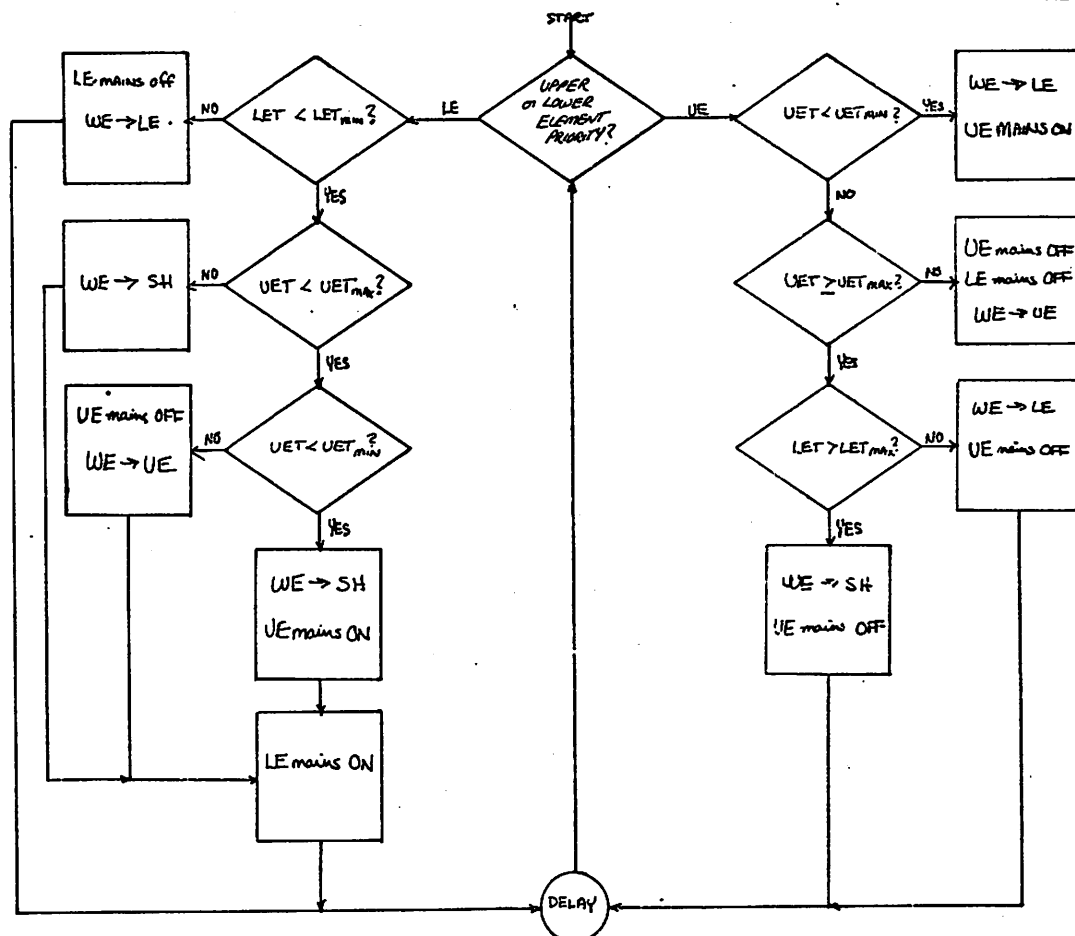
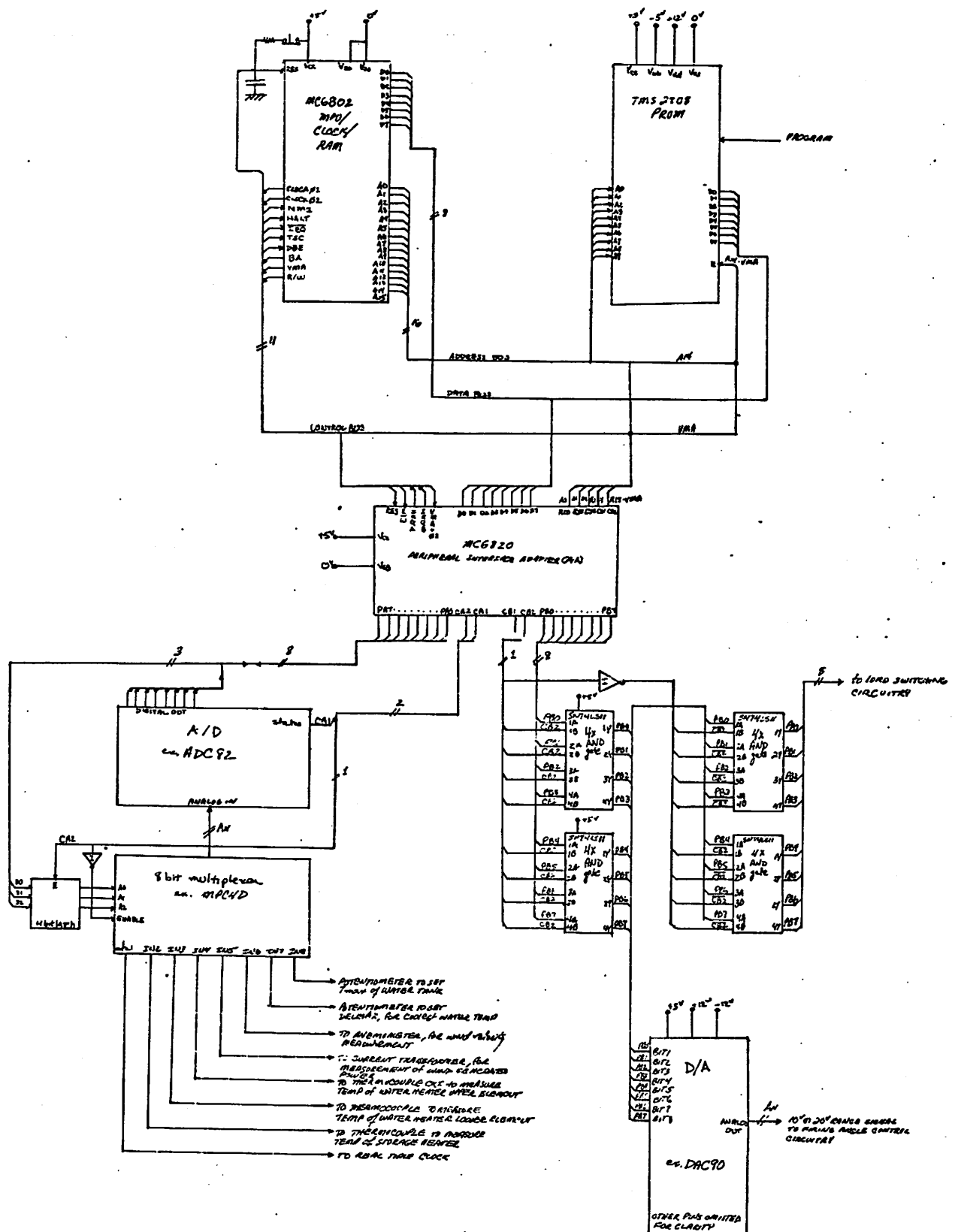


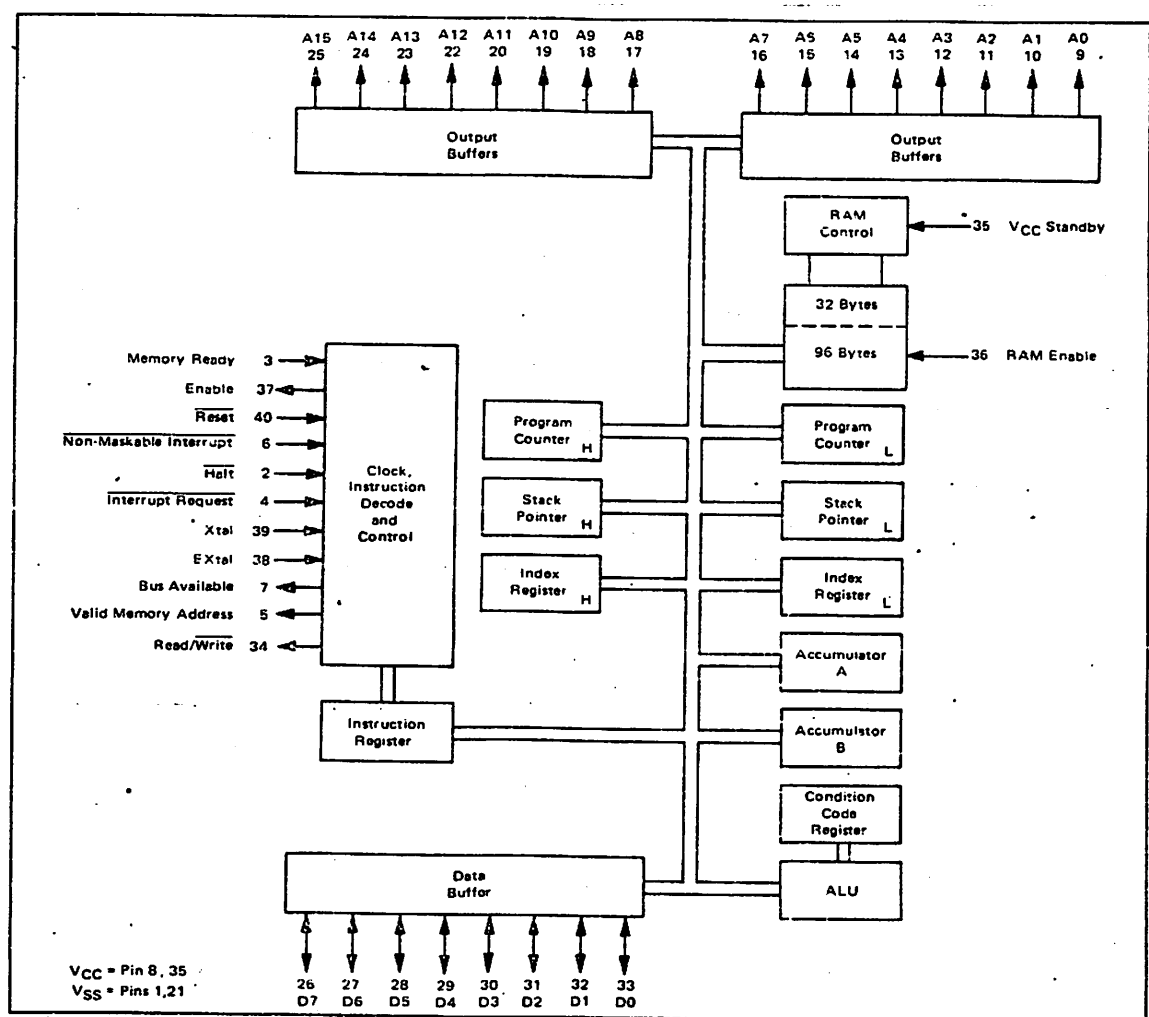
FIGURE 9. BLOCK DIAGRAM OF A LOAD MANAGEMENT CONTROLLER FOR A WIND ENERGY CONVERSION SYSTEM WITH A TWO ELEMENT WATER HEATER AND A STORAGE HEATER AS LOADS. NOTATION: WE = WIND ENERGY; LE = LOWER IMMERSION HEATING ELEMENT; LET = WATER TEMPERATURE AT LOWER ELEMENT; LETmin IS DEFINED BY FIGURE 8; UE, UET, UETmin AS IN LE, LET, LETmin BUT FOR UPPER ELEMENT; UETmin, UETmax ARE MAINS ELECTRIC SUPPLIES.



DATE OF ORIGINAL DRAWING 01/01/77	DATE 01/01/77
DESIGNED BY 10/01/77	DESIGNED BY 10/01/77
DRAWN BY 10/01/77	DRAWN BY 10/01/77
APPROVED BY 10/01/77	APPROVED BY 10/01/77
DATE OF REVISION 01/01/77	DATE 01/01/77
DESIGNED BY 10/01/77	DESIGNED BY 10/01/77
DRAWN BY 10/01/77	DRAWN BY 10/01/77
APPROVED BY 10/01/77	APPROVED BY 10/01/77

FIGURE 10.

FIGURE 11: MC6802 Expanded Block Diagram



MICROCOMPUTER CONTROLLER for a Small-Scale Wind Power System
(for heating domestic premises)

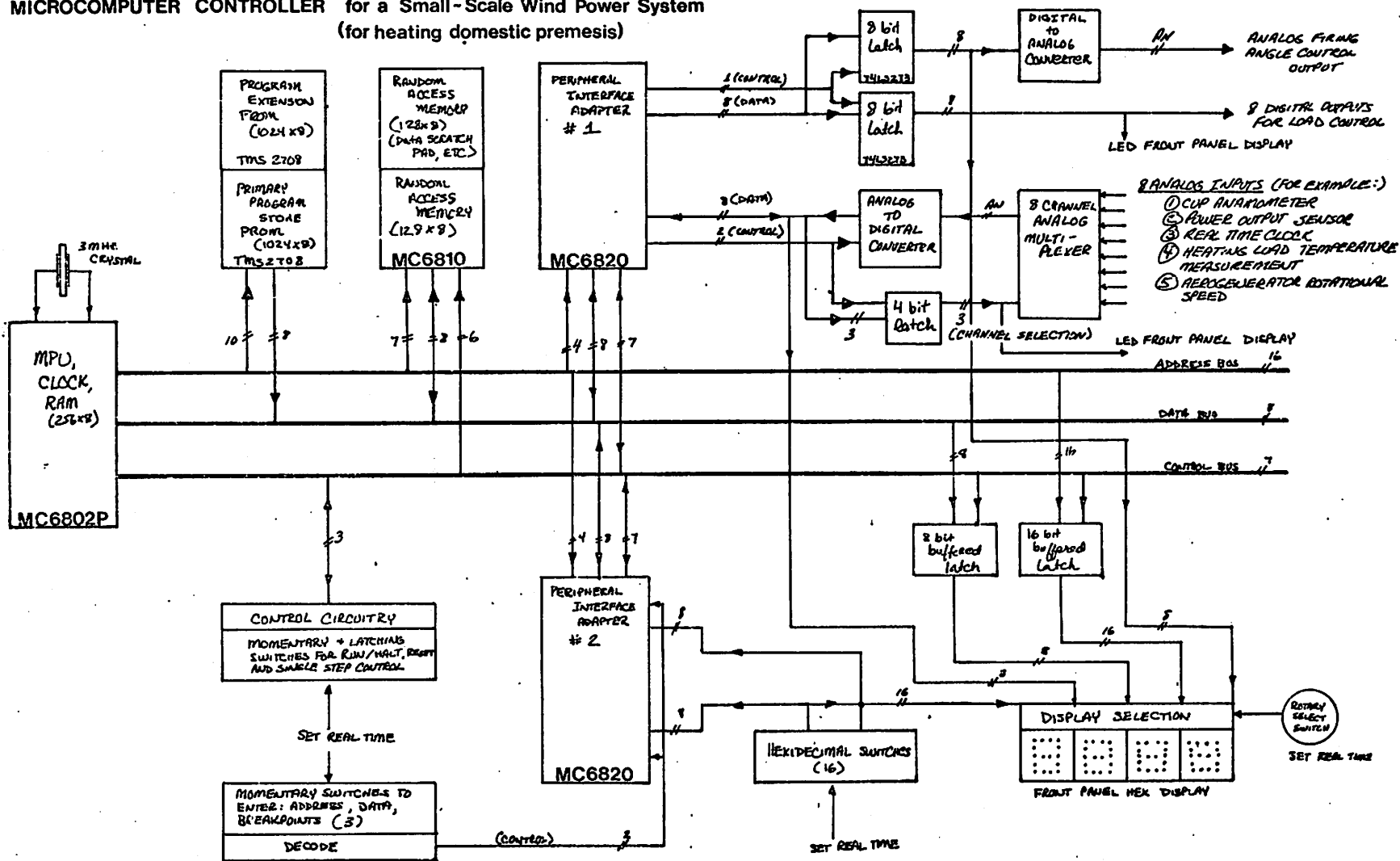


FIGURE 12.

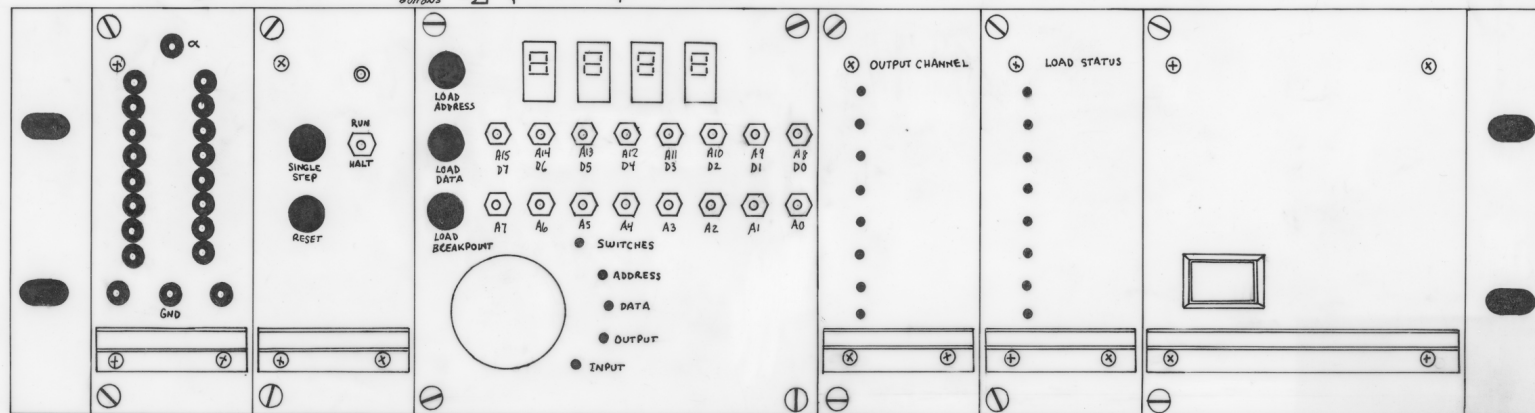
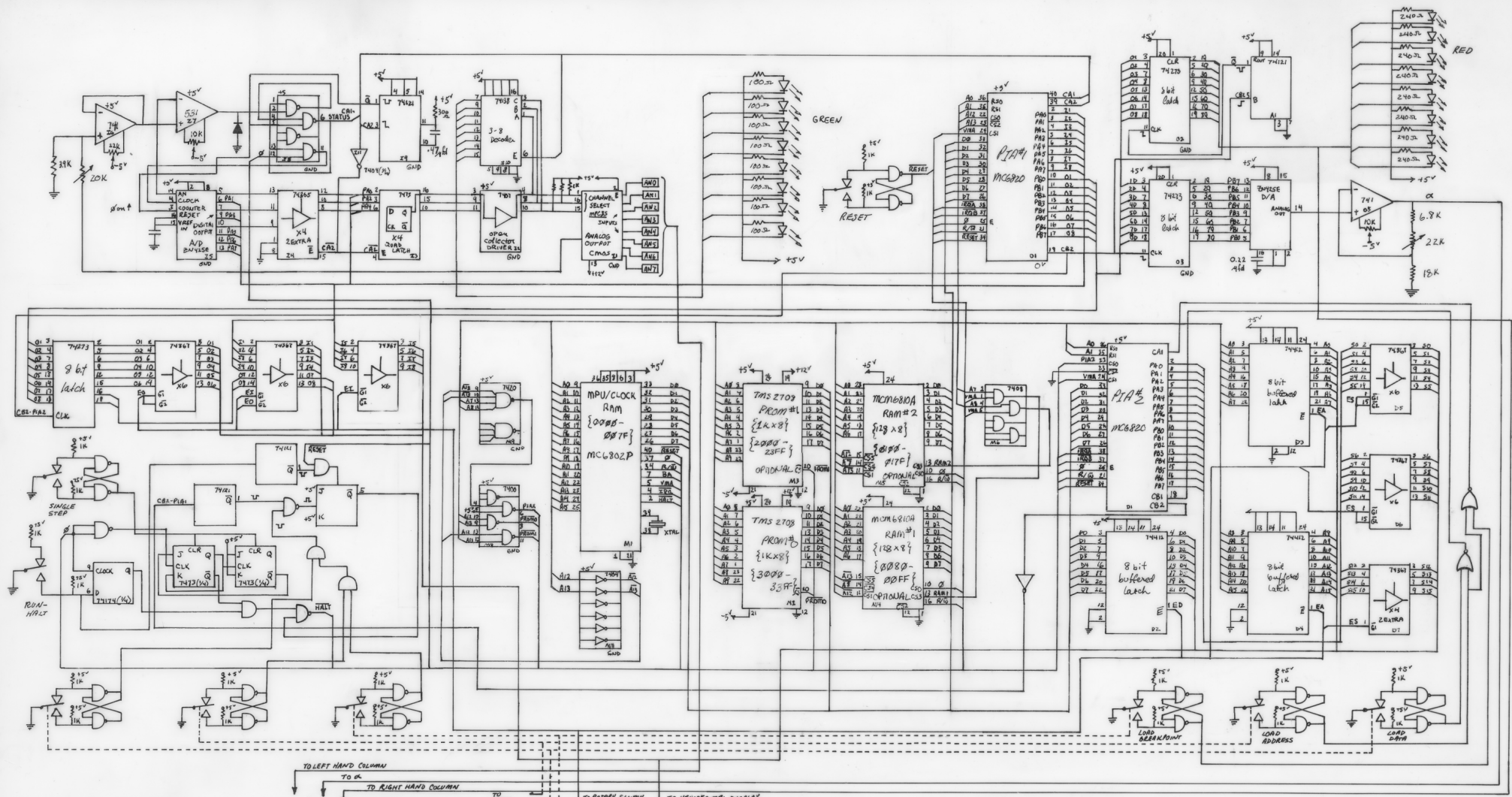
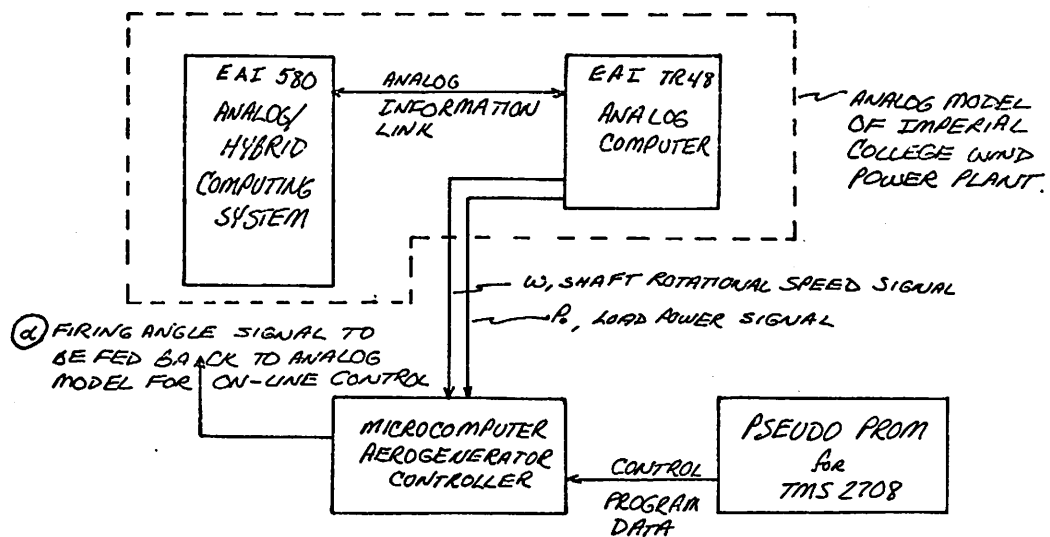


FIGURE 14. BLOCK DIAGRAM OF THE MICROCOMPUTER/ANALOG COMPUTER INTERCONNECTION.



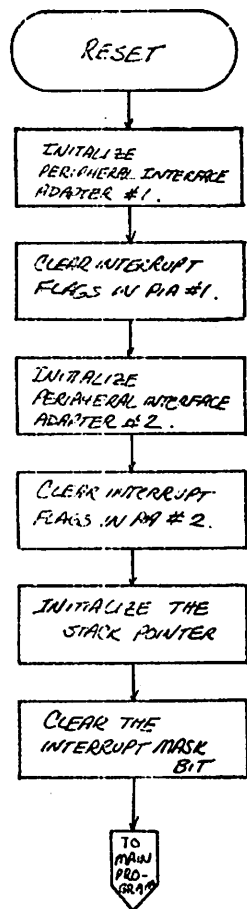


FIGURE 15. BLOCK DIAGRAM OF RESET ROUTINE

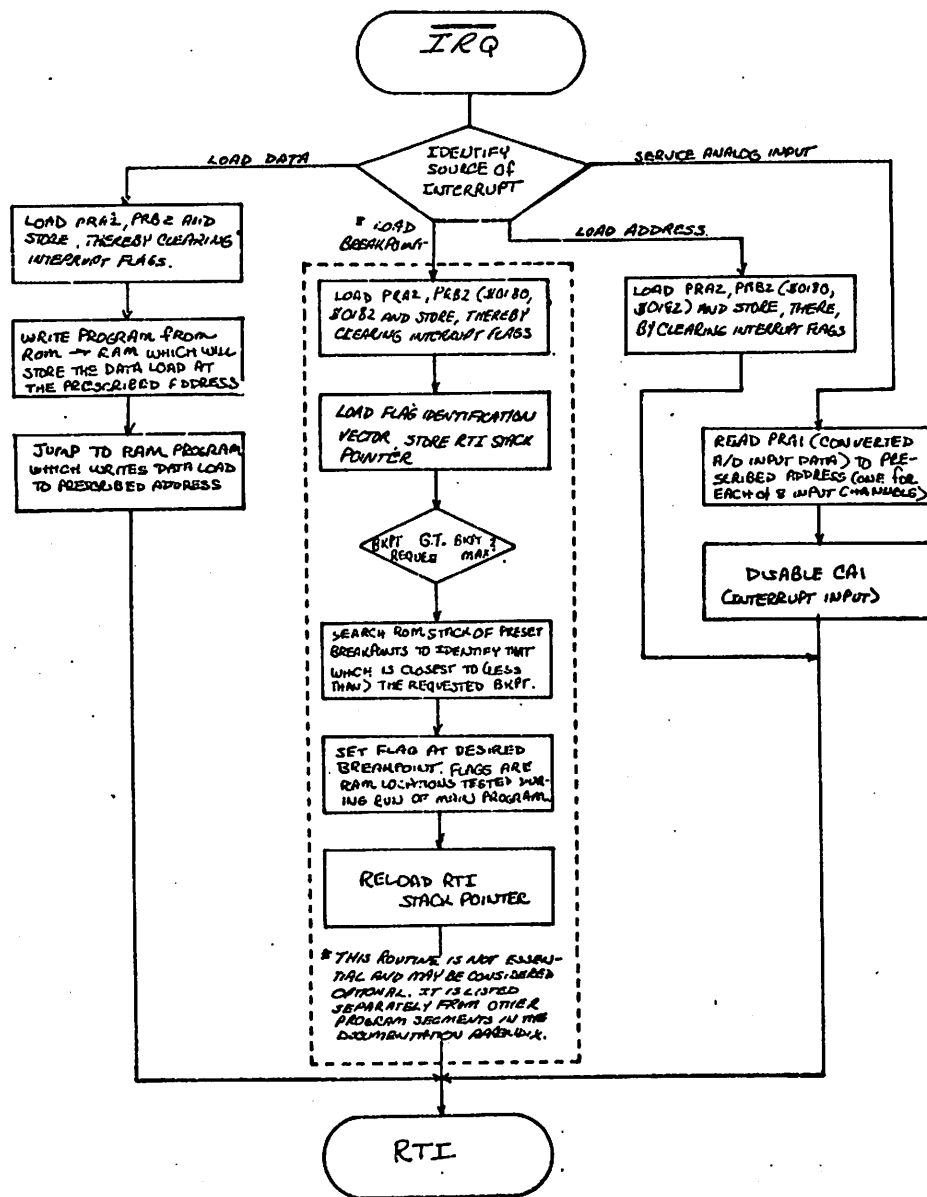


FIGURE 16. BLOCK DIAGRAM OF PROGRAM SEGMENT TO SERVICE INTERRUPT REQUESTS.

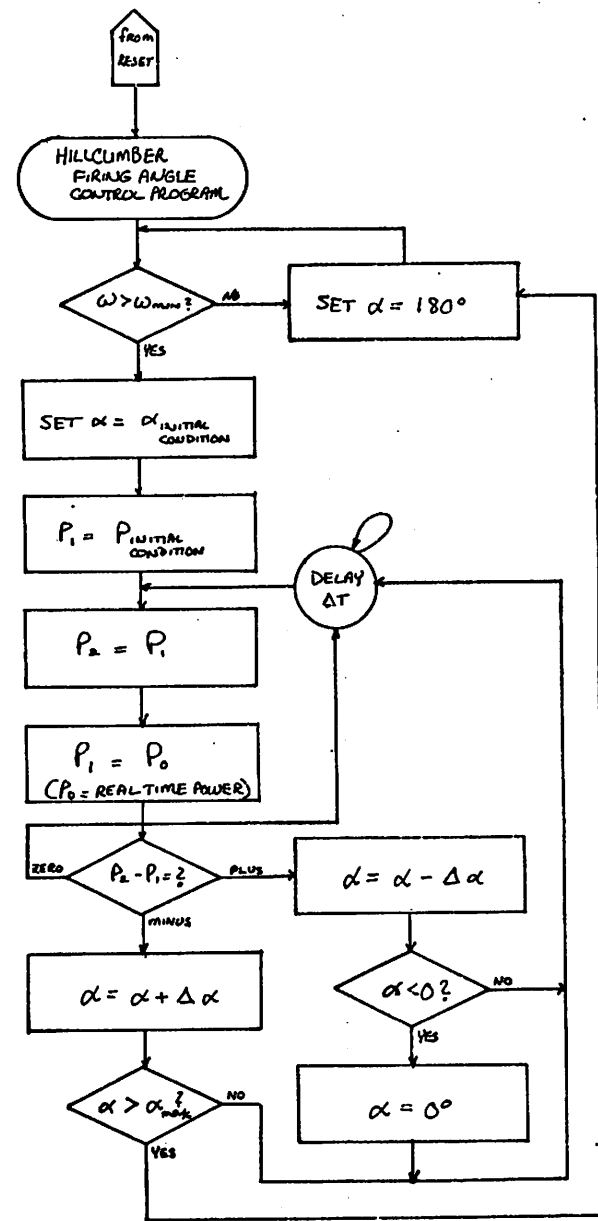


FIGURE 17. BLOCK DIAGRAM OF HILL-CUMBER FIRING ANGLE CONTROL PROGRAM

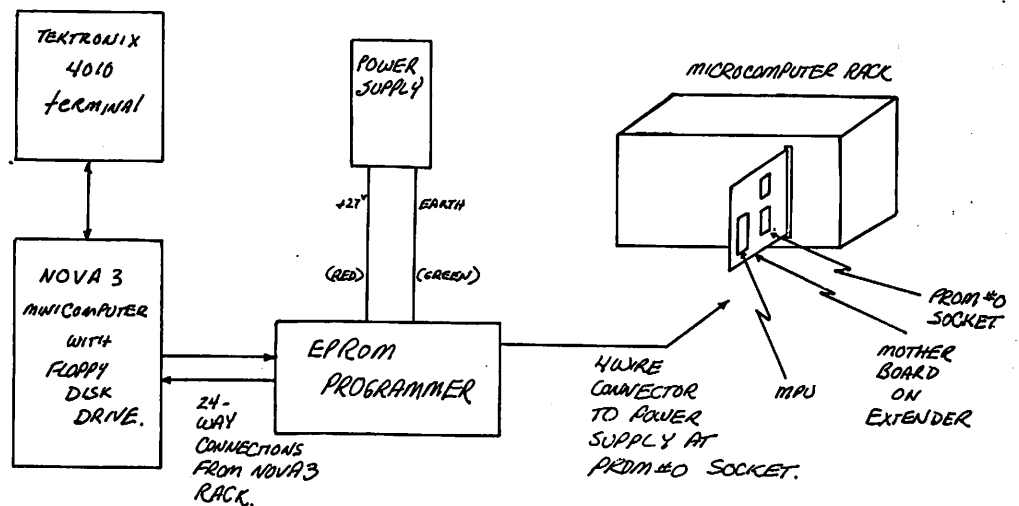
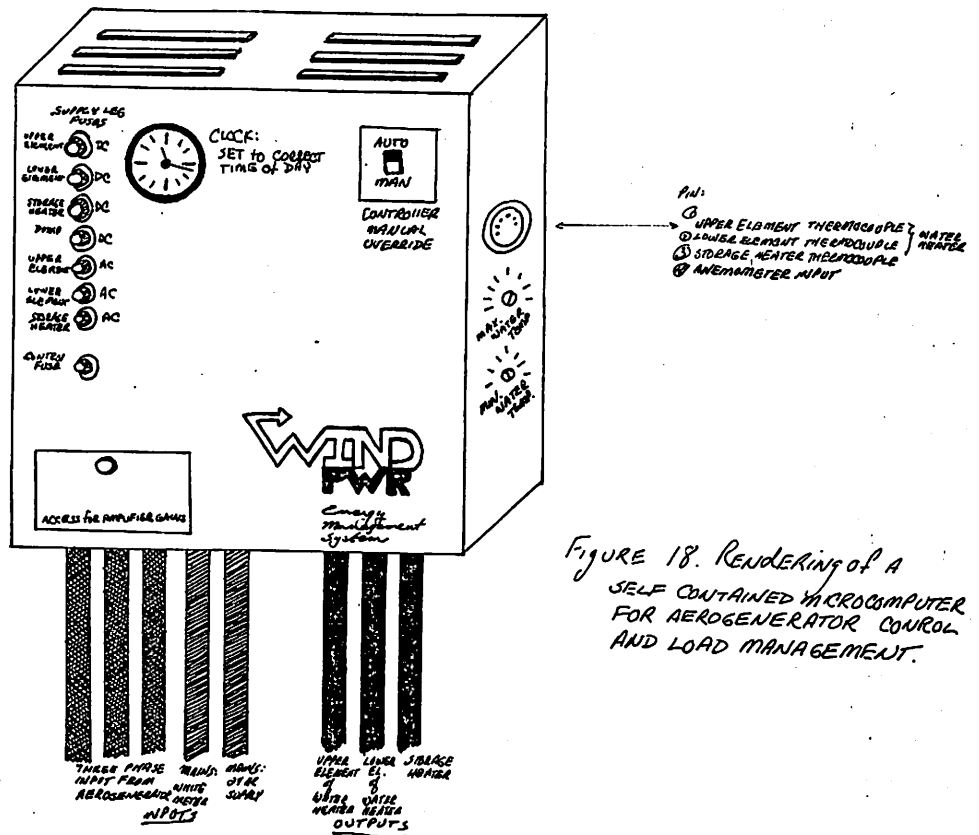


TABLE ONE
MICROCOMPUTER BOARD EDGE CONNECTIONS

Board Number	1	2	3	4	5
Pin Number	Mother	Output Control	Input Control	A,D,&S Display	I/O, R/H SS
1	+5v	+5v	+5v	+5v	+5v
2	-5v	-5v	-5v	-	-
3	+12v	out	+12v	-	-
4	A0	CB2-1	-	A0	CB2-1
5	A1	CB1-1	-	A1	-
6	A2	PB0-1	-	A2	PB0-1
7	A3	PB1-1	-	A3	PB1-1
8	A4	PB2-1	-	A4	PB2-1
9	A5	PB3-1	-	A5	PB3-1
10	A6	PB4-1	-	A6	PB4-1
11	A7	PB5-1	-	A7	PB5-1
12	A8	PB6-1	-	A8	PB6-1
13	A9	PB7-1	-	A9	PB7-1
14	A10	PA0-1	PA0-1	A10	PA0-1
15	A11	PA1-1	PA1-1	A11	PA1-1
16	A12	PA2-1	PA2-1	A12	PA2-1
17	A13	PA3-1	PA3-1	A13	PA3-1
18	A14	PA4-1	PA4-1	A14	PA4-1
19	A15	PA5-1	PA5-1	A15	PA5-1
20	-	PA6-1	PA6-1	-	PA6-1
21	-	PA7-1	PA7-1	-	PA7-1
22	HALT	CA1-1	CA1-1	-	HALT
23	-	CA2-1	CA2-1	CB2-2	CB2-2
24	PIA2	+12v	-	-	-
25	IRQ	IRQ	-	IRQ	-
26	A0	RS0-1	-	-	-
27	A1	RS1-1	-	-	-
28	RESET	RESET	-	RESET	RESET
29	D0	D0	-	D0	-
30	D1	D1	-	D1	-
31	D2	D2	-	D2	-
32	D3	D3	AN8	D3	-
33	D4	D4	AN7	D4	-
34	D5	D5	AN6	D5	-
35	D6	D6	AN5	D6	-
36	D7	D7	AN4	D7	-
37	-	-	-	-	-
38	-	-	AN3	-	-
39	VMA	CS1-1	AN2	CS1-2	-
40	A13	CS2-1	-	-	-
41	A12	CS0-1	AN1	CS0-2	-
42	R/W	R/W	-	R/W	-
43	0v	0v	0v	0v	0v

TABLE THREE
D/A CONVERTER CALIBRATION TABLE

		F/7	E/6	D/5	C/4	B/3	A/2	9/1	
FF	--	9.26	9.18	9.12	9.06	9.02	8.97	8.92	FF-F9
F8	8.87	8.85	8.80	8.75	8.70	8.68	8.62	8.59	F8-F1
F0	8.54	8.53	8.48	8.43	8.39	8.36	8.31	8.27	F0-E9
E8	8.23	8.21	8.16	8.12	8.07	8.05	8.00	7.96	E8-E1
E0	7.92	7.93	7.88	7.84	7.80	7.77	7.72	7.68	E0-D9
D8	7.64	7.62	7.57	7.54	7.49	7.46	7.42	7.38	D8-D1
D0	7.33	7.33	7.28	7.24	7.20	7.17	7.13	7.09	D0-C9
C8	7.05	7.03	6.98	6.95	6.90	6.87	6.83	6.80	C8-C1
C0	6.75	6.77	6.72	6.69	6.64	6.61	6.57	6.53	C0-B9
B8	6.49	6.47	6.43	6.39	6.34	6.31	6.30	6.23	B8-B1
B0	6.19	6.18	6.13	6.09	6.05	6.03	5.98	5.94	B0-A9
A8	5.90	5.88	5.84	5.80	5.75	5.73	5.68	5.65	A8-A1
A0	5.61	5.61	5.57	5.53	5.51	5.46	5.41	5.38	A0-99
98	5.34	5.32	5.27	5.24	5.19	5.17	5.12	5.09	98-91
90	5.05	5.03	4.99	4.95	4.91	4.88	4.84	4.80	90-89
88	4.76	4.74	4.70	4.66	4.62	4.59	4.55	4.51	88-81
80	4.47	4.52	4.48	4.43	4.39	4.36	4.32	4.28	80-79
78	4.24	4.24	4.17	4.13	4.09	4.06	4.02	3.98	78-71
70	3.94	3.92	3.88	3.84	3.80	3.77	3.73	3.69	70-69
68	3.65	3.63	3.59	3.55	3.51	3.48	3.44	3.40	68-61
60	3.36	3.36	3.32	3.28	3.24	3.21	3.17	3.13	60-59
58	3.09	3.06	3.02	2.99	2.95	2.92	2.88	2.84	58-51
50	2.80	2.78	2.74	2.70	2.66	2.63	2.59	2.56	50-49
48	2.52	2.49	2.45	2.42	2.38	2.35	2.31	2.27	48-41
40	2.23	2.24	2.20	2.16	2.12	2.09	2.05	2.01	40-39
38	1.97	1.94	1.90	1.86	1.83	1.80	1.76	1.72	38-31
30	1.68	1.66	1.62	1.58	1.54	1.50	1.47	1.44	30-29
28	1.40	1.37	1.33	1.30	1.25	1.22	1.19	1.12	28-21
20	1.10	1.10	1.06	1.02	.989	.954	.917	.881	20-19
18	.844	.813	.776	.740	.703	.669	.633	.597	18-11
10	.561	.531	.494	.458	.421	.387	.351	.315	10-09
08	.279	.248	.211	.176	.140	.106	.0704	.0353	08-01
00	.0000								

TABLE TWO
MC6820 INTERNAL ADDRESSING

RS1	RS0	Control Register Bit		Location Selected
		CRA-2	CRB-2	
0	0	1	X	Peripheral Register A
0	0	0	X	Data Direction Register A
0	1	X	X	Control Register A
1	0	X	1	Peripheral Register B
1	0	X	0	Data Direction Register B
1	1	X	X	Control Register B

X = don't care

TABLE FOUR
MICROCOMPUTER ADDRESS SPACE ALLOCATION

ADDRESS \ BIT	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	DEVICE
0000 - 007F	d	d	0	0	d	d	d	0	0	X	X	X	X	X	X	X	RAM #3 ON-BOARD MPU
0080 - 00FF	d	d	0	0	d	d	d	0	1	X	X	X	X	X	X	X	RAM #1
0100 - 017F	d	d	0	0	d	d	d	1	0	X	X	X	X	X	X	X	RAM #2
2000 - 23FF	d	d	1	0	d	d	X	X	X	X	X	X	X	X	X	X	PROG #1
3000 - 33FF	d	d	1	1	d	d	X	X	X	X	X	X	X	X	X	X	ROM #0
1000 - 1043	d	d	0	1	d	d	d	d	d	d	d	d	d	d	X	X	PIA #1
0180 - 0183	d	d	0	0	d	d	d	1	1	d	d	d	d	d	X	X	PIA #2

d = don't care

X = variable address

TABLE FIVE
RAM MAP £0000 - £007F

£0000:	-	£0062:	Wmin
£0001:	N1	£0063:	alpha initial cond.
£0002:	Nh	£0064:	power initial cond.
£0003:	Index Register (Xl)	£0065:	delta alpha
£0004:	Index Register (Xh)	£0066:	alpha maximum
£0005:	Acmltr A	£0067:	delay hi
£0006:	Acmltr B	£0068:	delay mid
£0007:	Condition Code	£0069:	delay lo
£0008:	SP	£006A:	input channel select
£0009:	-	£006B:	chnl 0 store
⋮		£006C:	chnl 1 store
£0053:	INX store (lo byte)	£006D:	chnl 2 store
£0054:	INX store (hi byte)	£006E:	chnl 3 store
⋮		£006F:	chnl 4 store
£005B:	P2	£0070:	chnl 5 store
£005C:	P1	£0071:	chnl 6 store
⋮		£0072:	chnl 7 store
£0060:	alpha output	⋮	
⋮		£007F:	-